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PROJECT REPORT

A FINITE ELEMENT ANALYSIS OF THE NPS AUTONOMOUS UNDERWATER VEHICLE (AUV) HULL INTENDED TO OPERATE IN DEEP WATERS

by
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July 2001

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A Finite Element Analysis (FEA) of the hull is used. FEA is the most common structural analysis tool. This report illustrates the different steps made to process the FEA.

A first analysis is performed to check the structural behavior of the hull for shallow waters (until 100feet). A second analysis is made for deep waters. Some solutions to strengthening the hull are presented. Several type of stiffeners can be used.

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A FINITE ELEMENT ANALYSIS OF THE NPS AUTONOMOUS UNDERWATER VEHICLE INTENDED TO OPERATE IN DEEP WATERS.

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Ecole Nationale d'Ingénieurs de Tarbes

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From the

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ABSTRACT

The Naval Postgraduate School AUV, named ARIES, was intended to operate in shallow waters. Its utilization as a server vehicle can requires to dive deeper. The purpose of this project is to check if the structure of the ARIES is able to go in deep diving depth.

A Finite Element Analysis (FEA) of the hull is used. FEA is the most common structural analysis tool. This report illustrates the different steps made to process the FEA and to obtain an accurate model.

A first analysis is performed to check the structural behavior of the hull for shallow waters (until 100feet). A second analysis is made for deep waters. Some solutions to strengthening the hull are presented. Several types of stiffeners can be used.

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I would like also to thank my project supervisor in France, Jean-Yves Fourquet.

I. INTRODUCTION

A. BACKGROUND

The center for Autonomous Underwater Vehicles (AUV) research of the Naval Postgraduate School (NPS) of Monterey explores many concepts in design, AUV control systems and Command and Control research. An AUV is a self-contained unmanned vehicle used for missions such as surveying or data gathering. The AUV developed by NPS, the ARIES (Acoustic Radio Interactive Exploratory Server), is used also as a communication server vehicle.

B. MOTIVATIONS AND GOALS

The main attribute of a submarine is its ability to dive beneath the surface and to go to reasonable operating depth. ARIES is intended to shallow waters. The focus of this work has been to test depth capability of the ARIES on a structural aspect. A FEA (Finite Element Analysis) has been performed to examine the structural response of the hull at loads due to the depth.

A first step is to check and observe structural behavior of the hull in shallow waters until 100feet. The goal is to reach 300feet below the sea surface. It will probably needs stiffeners to operate at this depth whereas the hull is subjected to high pressure and bending moments. Strengthening hull has been studied.

C. ORGANIZATION OF THE REPORT

This report is organized into seven chapters.
Chapter I is the present introduction.

Chapter II is a general overview of the ARIES, the NPS AUV. It provides a vehicle description and a presentation of computer architecture, navigation and the use of ARIES as a network server

Chapter III is a detailed problem statement. The structural problems related to deeper water operations are briefly exposed.

Chapter IV gives preliminary information about the FEA.

Chapter V details the FE model designed and presents how the model has been made. Key components of the FE process are described: mesh design, boundary conditions, checks and other parameters of the FEA.

Chapter VI provides the analysis results and the structural response of the hull at 100feet and 300feet.It presents different kind of stiffeners intended reinforcement of the hull.

Finally chapter VII summarizes conclusions and observations of the analysis and presents recommendations for future work.

II.RELATED WORK

This part provides an overview of the ARIES. It contains a physical description, mechanical and informatics concept and current developments. This chapter is based on the paper titled “current developments in underwater vehicle control and navigation – The NPS ARIES AUV” written by David B. Marco and Anthony J. Healey [1].

A. INTRODUCTION

The NPS center for AUV research has been building and researching AUV since 1987. The current vehicle named ARIES is the third generation of NPS AUV. Its construction started in 1998. First intended for mine reconnaissance the NPS AUVs is now used as a server in a multi-vehicle environment. ARIES replaces the PHOENIX vehicle intended only to data gathering. It proposed to used ARIES as a mobile communications relay between multiple vehicles operating and a command and control station located in the surface.

ARIES missions include data gathering, data transfer, surveillance and communication with other vehicles. It has the capability of bottom following, track following with acoustic and videos imaging.

This chapter provides a global overview of the ARIES focusing on mechanical description, computer hardware and software architecture and navigation. The last part is a presentation of the ARIES as a network server vehicle.

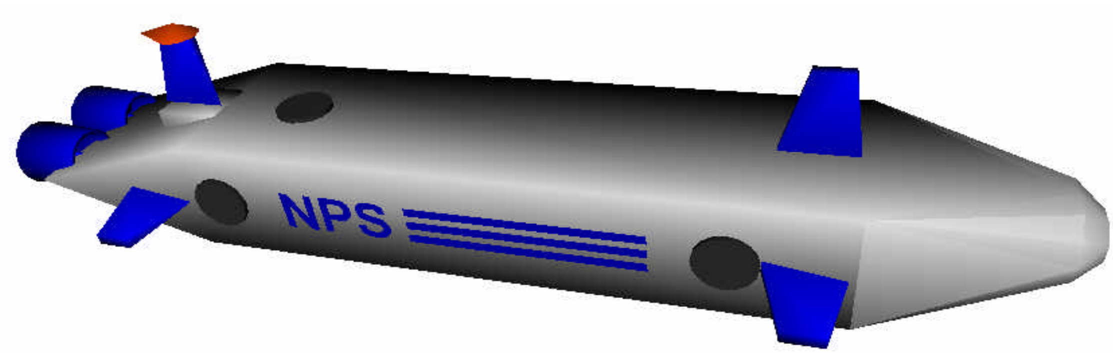


Figure II -1: 3D ARIES model

B. VEHICLE DESCRIPTION

1. Dimensions and endurance

ARIES is approximately 3m long, 0.4m wide and 0.25m high. The hull is constructed of ¼” thick 6061 aluminum and it weighs 220Kg. A flooded fiberglass nose is used to house the external sensors and power on/off switches and status indicators.

The vehicle has a top speed of almost 4 knots. The ARIES was primarily designed for shallow water operations and can operate safely down to 30 meters. However, with hull strengthening in certain areas, a depth of 100 meters may be attained.

ARIES is powered by six 12 volt rechargeable lead acid batteries. The endurance is approximately 4 hours at top speed, 20 hours hotel load only

2. Propulsion and Motion Control Systems

Main propulsion is achieved using twin ½ Hp electric drive thrusters located at the stern. During normal flight, heading and depth is controlled using upper bow and stern rudders and a set of bow planes and stern planes. Since the control fins are ineffective during very slow or zero forward speed maneuvers, vertical and lateral cross-body thrusters are used to control surge, sw and propulsion systemsay, heave, pitch, and yaw, motions.

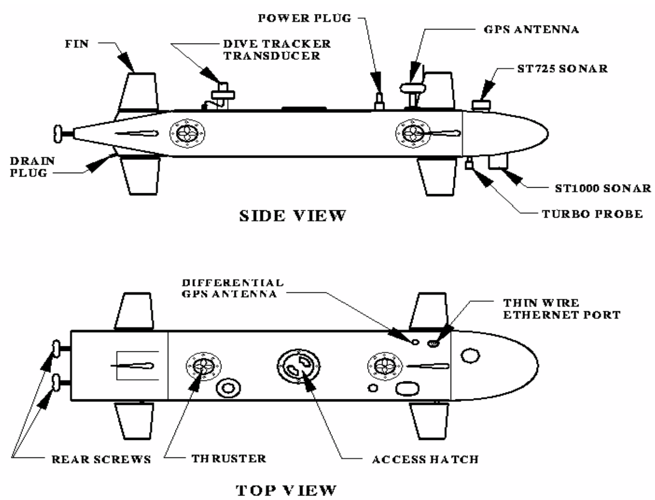


Figure II -2: localization of main sensors and propulsion systems

3. Navigation sensors

The sensor suite used for navigation includes a 1200 kHz RD Instruments Navigator DVL that also contains a TCM2 magnetic compass. This instrument measures the vehicle ground speed, altitude, and magnetic heading. Angular rates and accelerations are measured using a Systron Donner 3-axis Motion Pak IMU. While surfaced, carrier phase differential GPS (DGPS CP) is available to correct any navigational errors accumulated during the submerged phases of a mission.

4. sonar and video sensors

A Tritech ST725 scanning sonar or an ST1000 profiling sonar is used for obstacle avoidance and target acquisition/reacquisition. The sonar heads can scan continuously through 360^{o} of rotation or swept through a defined angular sector. A fixed focus wide-angle video camera is located in the nose and connected to a DVC recorder. The computer is interfaced to the recorder and controls on/off and start/stop record functions. While recording, the date, time, vehicle position, depth and altitude is superimposed on the video image.

5. Vehicle/operator communication

Radio Modems are used for high bandwidth command, control, and system monitoring while the vehicle is deployed and surfaced. While submerged, an acoustic modem is used for low bandwidth communications. In the laboratory environment, a high-speed thin-wire ethernet connection is used for software development and mission data upload/download.

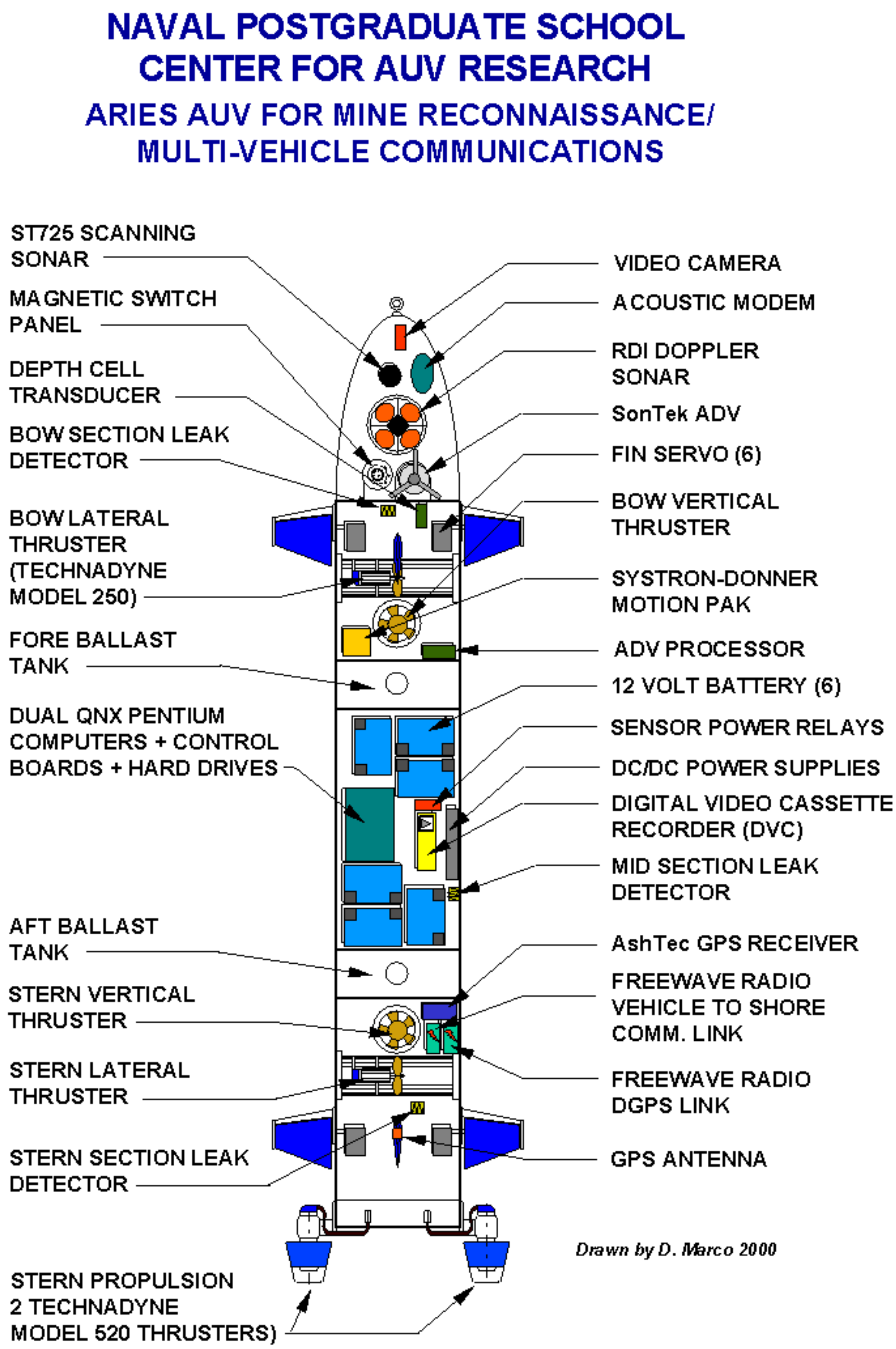


Figure II -3 : hardware components of the NPS ARIES

C. COMPUTER HARDWARE ARCHITECTURE

A photograph of the dual computer system unit is shown in Figure II.4 and measures approximately 28 x 20 x 20 cm. It consists of two Ampro Little Board 166 MHz Pentium computers with 64 MB RAM, four serial ports, a network adapter, and a 2.5 GB hard drive each. Two DC/DC voltage converters for powering both computer systems and peripherals are integrated into the computer package. The entire computer system draws a nominal 48 Watts.

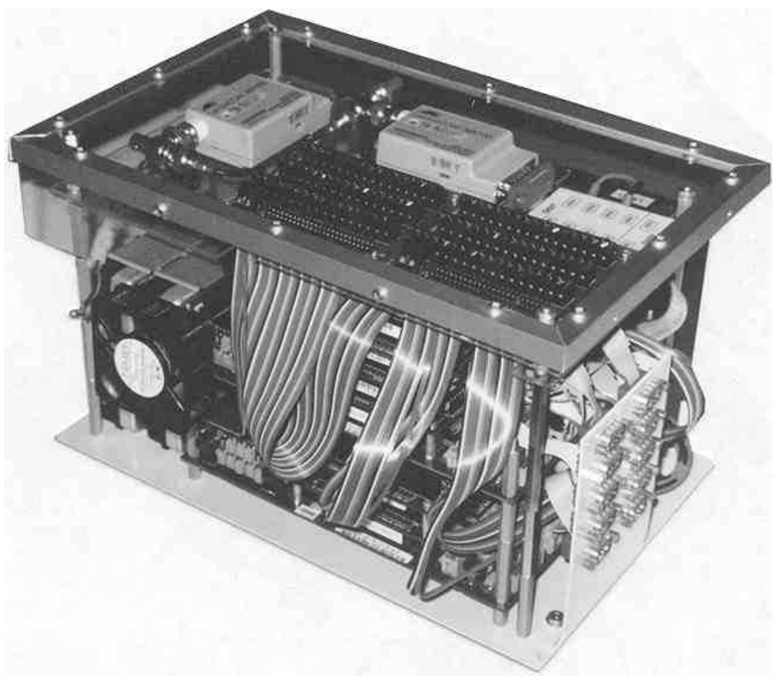


Figure II -4. Dual Computer System Unit

Both systems use TCP/IP protocol for internal and external communications. The computer designed to gathering data The sensor data gathering computer is designated QNXT, while the second is named QNXE and executes the various auto-pilots for servo level control

The figure next page shows this dual computer software architecture.

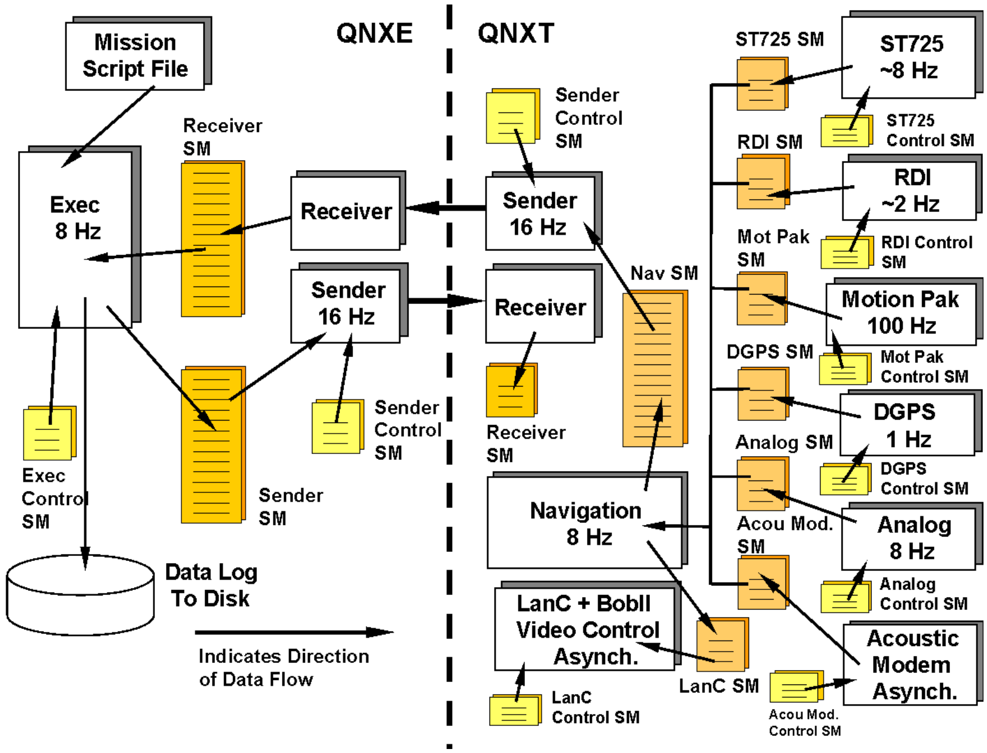


Figure II -5 : Dual Computer Software Architecture

D. COMPUTER SOFTWARE ARCHITECTURE

Both computers run the QNX real time operating system using synchronous socket sender and receiver network processes for data sharing between the two. All processes are written in the C programming language.

ARIES use a software architecture with 3 levels called Rational behavior Model (RBM). It divides responsibilities into areas of open-ended strategic planning, soft-real-time tactical analysis, and hard real time execution level control. The RBM architecture has been created as a model of a manned submarine operational structure.

The correspondence between the three levels and a submarine crew is shown in the Figure II.6

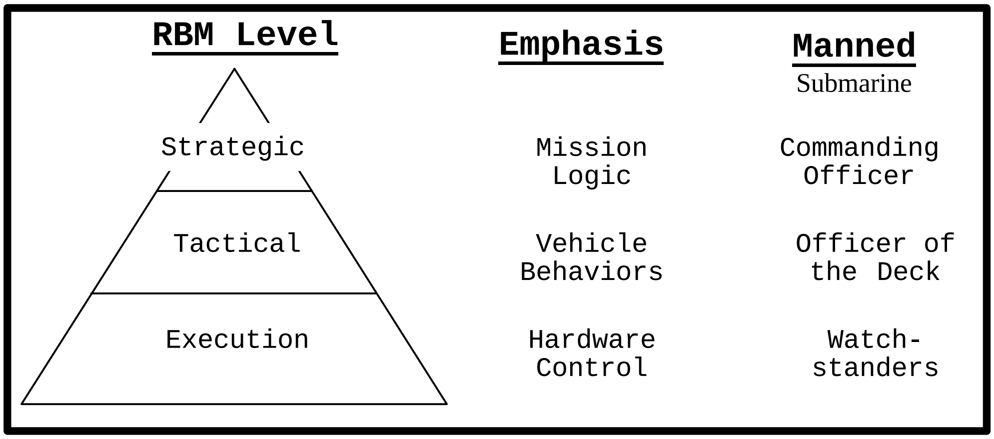


Figure II -6 : The Relational Behavior Model tri-level architecture hierarchy with level emphasis and submarine equivalent listed [Holden 95].

The **Execution Level** assures the interface between hardware and software. Its tasks are to provide the motion stability of the vehicle, to control the individual devices, and to provide data to the tactical level.

The **Tactical Level** provides a software level that interfaces with both the Execution level and the Strategic level. Its chores are to give to the Strategic level indications of vehicle state, completed tasks and execution level commands. The Tactical level selects the tasks needed to reach the goal imposed by the Strategic level. It operates in terms of discrete events.

The **Strategic Level** controls the completion of the mission goals. The mission specifications are inside this level

E.NAVIGATION

The ARIES vehicle uses an INS / DOPPLER / DGPS navigational suite and an Extended Kalman Filter (EKF). The main data required to navigational accuracy are the heading reference and the speed over ground measurement. In this system, the heading reference is derived from both the compass located in the RDI Navigator and the Systron Donner IMU, which provides yaw rate. The fusion of the yaw rate and the compass data leads to an identification of the yaw rate bias which is assumed to be a constant value. The compass bias is identified in the EKF using DGPS positions when surfaced.

When submerged, the position error covariance grows, but is corrected on surfacing. A relatively short surface time, (for example, 10 seconds) allows the filter to re-estimate biases, correct position estimates and continues with improved accuracy.

` As a demonstration, the ARIES vehicle was operated in Monterey Bay, June 2000, in a series of runs including a dive-surface-dive-surface sequence. The figure below shows a plot of vehicle position where the solid line to the left indicates the dead reckoning solution and the line to the right represents the EKF solution.

In this plot, the vehicle trajectory starts at (0,0) turns counterclockwise underwater and proceeds in a northerly direction for 100 meters, surfaces and takes DGPS measurements, submerges and travels an additional 100 meters and finally surfaces.

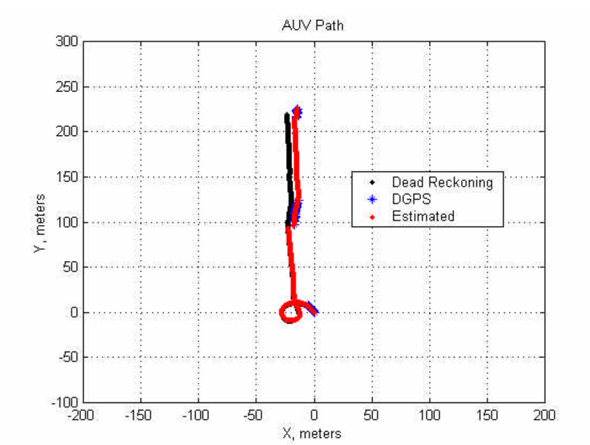


Figure II 0-7. Circular Dive - Underwater Segment - Surface - Dive - Surface Mission. Red Segments are the EKF Solution, Black - The Dead Reckoning Solution, and Blue * are DGPS Values.

In the second figure, a close up of the final surfacing maneuver shows that there is only a sub meter error in attaining the true DGPS data point. The solid line to the left again indicates the dead reckoning solution which is several meters off the mark.

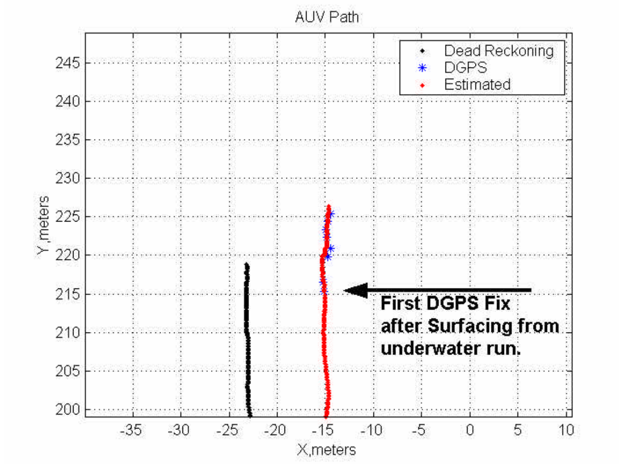


Figure II -8 : DGPS Data in Blue * with EKF Solution in Green. Segments without the Blue * Correspond to Underwater Segments

F. SERVER VEHICLE CONCEPT

It is proposed to use the NPS ARIES as a network server vehicle for multi-vehicle cooperative operations. One of the needs is underwater data transfer between network nodes through noisy communication channels. Use of the server vehicle as a data relay increases the range of communications of the underwater components of the network.

. Figure II.9 describes the concept where in position 1, the ARIES communicates through its acoustic modem with multiple worker vehicles that are engaged in a search pattern. Position 2 shows the ARIES on the surface using a radio modem to report mission status of the worker vehicles (possibly vehicle positions, image snippets of targets, and hydrographic data) to the command ship. While surfaced the server vehicle can receive tactical decision re-tasking commands. Once the new orders are received, the vehicle will submerge and transmit, using its acoustic modem, new tasks to each worker vehicle. Using a server vehicle eliminates the complexity of deploying fixed buoys

Also, a vehicle of this type can achieve close proximity or rendezvous with the worker vehicles allowing for higher acoustic bandwidth data transfer

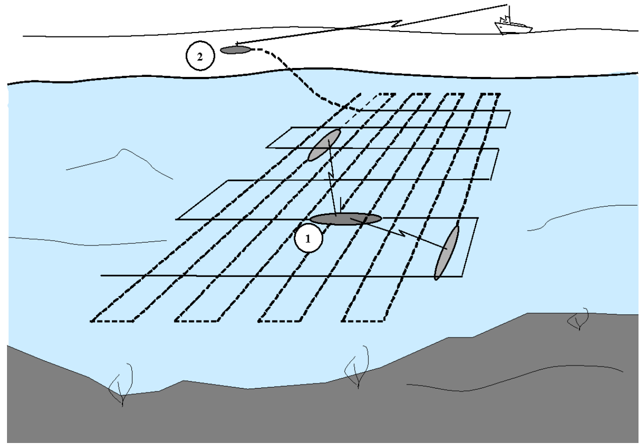


Figure II-9 : Sever vehicle concept. 1. Low bandwidth submerged data transfer between underwater vehicles. 2. High-speed data relay to command ship

Clearly, common communications protocols are needed in order to make this concept viable. Therefore, each vehicle in the network must share a common control language. For instance an agreement could be made to use a set of NEMA type command strings to set waypoints, tracks, behaviors, and status inquiry.

III PROBLEM STATEMENT

A INTRODUCTION

A structural analysis of the hull is required in order to improve the depth limit and the field of ARIES operations. F.E.A is preconsized before prototyping. Indeed, it is necessary to check the structural behavior of the hull by simulating. Boundary conditions have to be determined. The problem is that pressure damages the hull. The analysis is performed for shallow and deep waters.

B OVERVIEW OF THE PRESSURE EFFECTS ON THE AUV

The next picture shows the external aspect of the vessel:

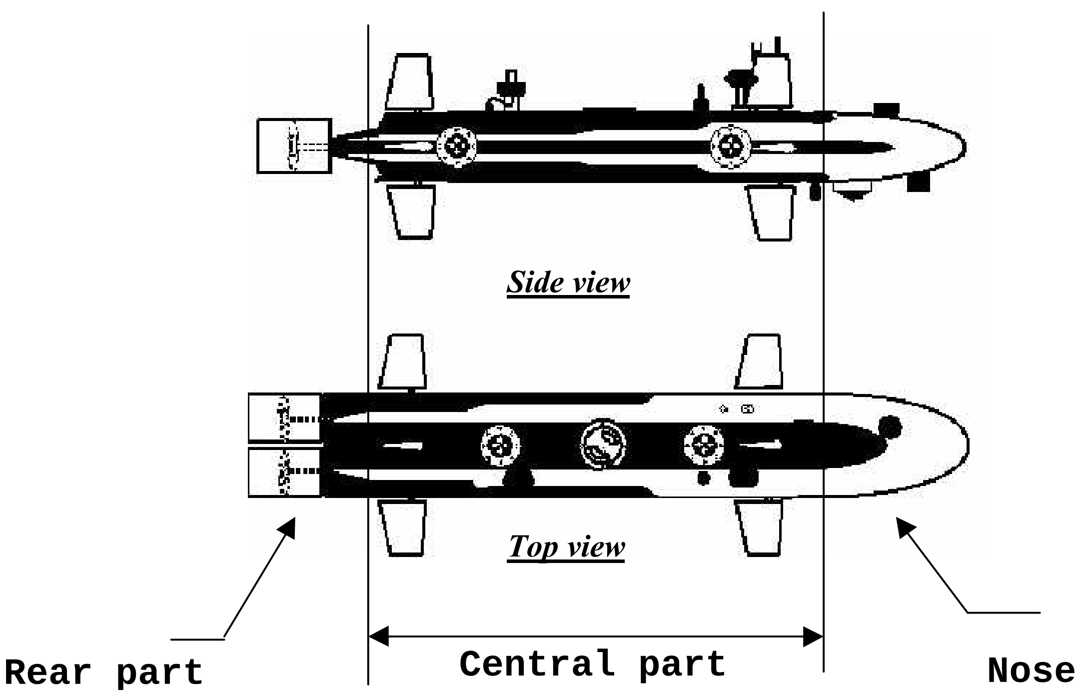


Figure III -1 AUV external view

The shape of the AUV is separated in three compartments: central part, rear part and nose. Only the central part has to be studied.

It is not worth analyzing the stresses and the deflections due to the pressure on the rear part. There are also no structural problems under water static pressure. A flooded fiberglass nose is added that’s why it does not take place in the study.

Figure III -2 : ARIES hull

The hull is made in aluminum 6061,1/4” thickness.

Main stresses and main deflections are expected in the part located between the two ballast tanks. In this area there is an opening in the hull to install the electronic and informatics systems. A center hatch plate is used to latch all the stuffs inside. This part of the hull is the most solicited because the hatch plate highly damages the hull by applying more forces due to the water pressure. Hence, it sufficient to study only this part of the hull so the F.E.A is focused on its model:

The results obtained allow to understand and evaluate the effects of water pressure on the whole hull.

The next figure shows exactly the part of the A.U.V to study.

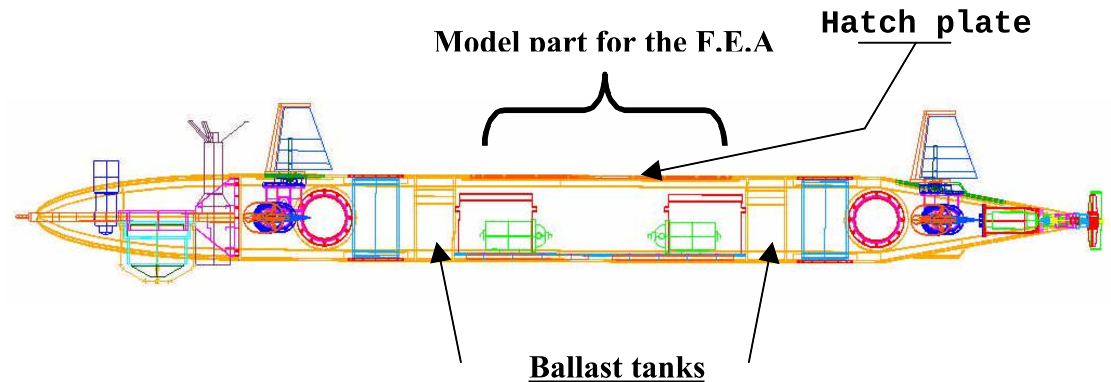


Figure III-3: A.U.V part analyzed

C BEHAVIOR ASSUMPTIONS

Loaded with high-pressure, the bottom, the lateral faces and the top face of the hull bend. Deflection expected in the bottom is nearly ¼ inch. Main stresses suppose to be located in the corners of the upper face and on the lateral edges (up and down).

D STEPS OF THE ANALYSIS

A F.E.A is performed to solve this problem. After the design of an accurate model, the first step is to ensure that the structure resists to the loads at 100 feet. It seems that the ship is not able to dive deeper without strengthening the hull. Different kinds of stiffeners have to be tested. After analysis, a valid solution has to be selected.

IV PRELIMINARY INFORMATION

A. JOB SPECIFICATION

The finite element model (F.E.M) is based on the drawings designed by D.Marcos and converted by S.Garribal into IDEAS files.
The files are available in octane3, directory: vault5/abeis/FEA.
A complete list of the files is provided in appendix C.

The job specification calls for a static, linear elastic, finite element analysis (F.E.A) of frames from parts of the hull of the ARIES Autonomous Underwater Vehicle.

The purpose of the analysis is firstly to check the depth that the hull is currently able to dive in shallow waters and secondly to study his comportment at the depth of 300feet. Thanks the results of the F.E.A, stiffeners will be incorporated to the hull. The goal is to perform until 300feet without structural problems.

The acceptance criteria for the analysis are:

- Maximum stress not to exceed material yield stress (aluminum 6061: yield stress is 40400 PSI)
- Localized stress in excess of yield stress are considered acceptable

B. RATIONALE FOR USING FOR F.E.A

The structure is too complex to be analyzed by hand calculation. Even if F.E.A is a mathematical approximation of a model, results provided by this method are pretty similar than tests. If each sample was built and tested, the costs and time will be far superior to this simulation method. F.E allows optimized performance before prototyping and developing.
F.E.A results give lot of indications about stresses, displacements within the model. This is a good way for predicting failures.

C. F.E.A SOFTWARE

I-DEAS Master Series 6 developed by SDRC was used for the geometric models designs and the finite elements works performed. It works on Silicon Graphics station, (Unix protocol).

D. BRIEF OVERVIEW OF F.E.A

1. Introduction:

F.E.A consists of a computer model of a design that is stressed and analyzed to get specific results: stresses, displacements and structural behavior of the part … This is a numerical procedure for obtaining approximate solutions. Also this is possible to determine modifications on the design of the part from analysis results and to incorporate them into the F.E.A.

2. How does it work?

In the F.E method the part to study is discretized into simple geometric shapes (elements), which make a grid called mesh. The mesh is programmed to contain the material and the structural properties that define how the structure will react to loading conditions. A complex system of nodes links the elements of the mesh.

Boundary conditions are applied to the model: displacements, forces and moments, pressures, temperatures, inertia loads.
F.E program assembles the stiffness matrices for these elements together to create the global stiffness matrix, related forces to displacement: $\{F\} = [K] \times \{d\}$

It is followed by solving the matrix for the unknown displacements, given the known forces and boundaries conditions, then the updating of the displacement value for each node within the model. The stresses in each element can be calculated.

3. Main steps of F.E.A

a. Pre-processing:

The user has to realize the following tasks:

- Create a geometric model in a CAD
- Enter physical and material properties
- Design the meshing
- Apply the boundaries conditions
- Check the model

b. Solution:

F.E program solves the equations. Different types of analysis are possible: linear, non-linear, dynamics… . The next step is to check the solution.

c. Post-processing:

Checks have to be in the post processor task:

- Solve the errors and the warnings
- Ensure that the results are consistent with expectations by analyzing and checking the results plotted.

-Then the user has to valid or not the F.E.A.

V F.E. MODEL

A. GENERAL INFORMATION

1. Analysis type

The purpose of the analysis is to examine the stress concentrations and the behavior of the structural models under static loads. Therefore the problem is static and non-linear.

Drawings, frames and F.E.A are in 3D to describe the structural behavior. The analysis is assumed to be linear since the stresses are limited to the yield stress. Dynamic solution is not within the scope of the study.

The drawings and the frames are an idealization of the parts of the structure to perform the F.E.A. The unmodelled structures have a small influence on the results.

2 Units and axis

US units were used throughout the F.E.A. Therefore the units of length, area, moment of inertia and Young's modulus were inch, inch^2, inch^4 and PSI. Stresses are exprimed in PSI.

The global coordinate system for the problem is as follows:

Global X axis: athwartship

Global Y axis: vertical

Global Z axis: parallel to centerline

B. GEOMETRIC MODEL

The overall strength of the hull is the primary focus of this analysis. The hatch plate will be studied too. A physical description of the ARIES is provided in chapter II. Here there is a brief geometric aspect overview of the models used for the analysis

a. Hatch plate

The hatch plate is made in Aluminum 6061, ¼ inch thick , 30.5 inch long and 11.5 inch wide.

b. Hull

The model used is not the whole hull. As seen above the model for this analysis is the part located between the ballast tanks. The thickness is obviously ¼ inch.

The whole model is 10 inch high, 16 inch wide and 34.5 long. Curved transitions have a fillet of 1.25inch. The opening in the top face is 9.8inch wide and 28.8 long.

Carter and half models are issued from the applying of symmetric conditions. Indeed, symmetry is assumed about two vertical planes in longitudinal and transversal cuts.

The next figure presents the model in three-dimensional:

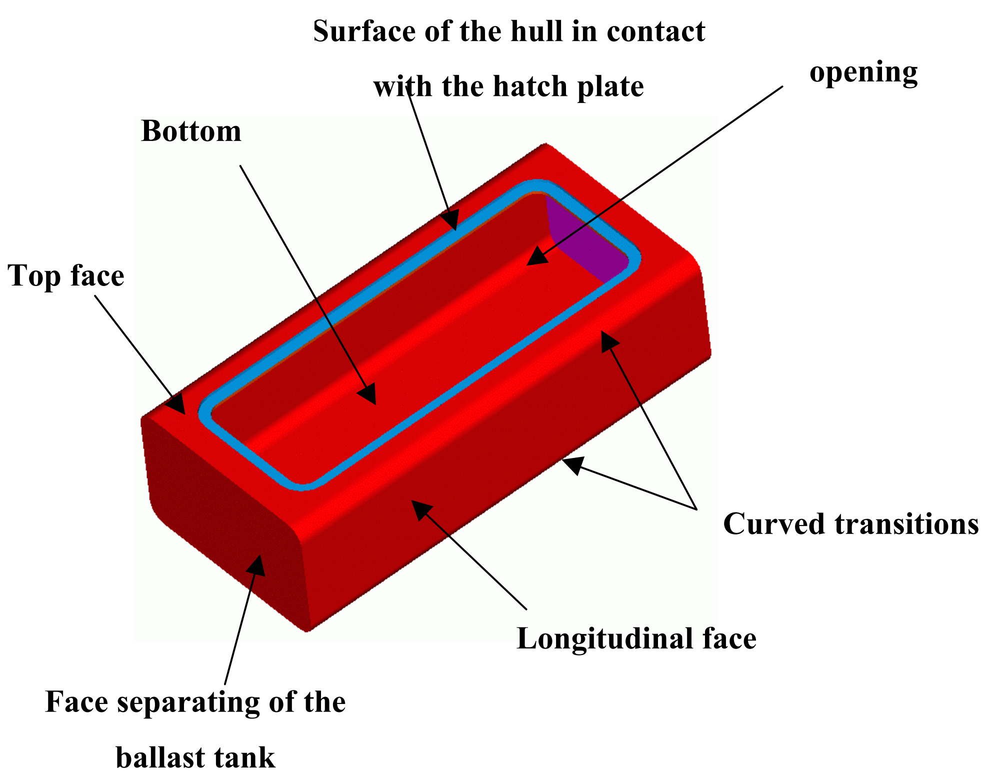


Figure V -1 : model part in 3D

C. MATERIAL PROPERTIES

Aluminum 6061 was chosen to make the hatch plate and the hull. The failure criteria applied is yield stress whereas this is an isotropic material. This is an aluminum alloy, nonferrous metal, classified in 6000 Series Aluminum alloy. ISO classification is AlMg1SiCU. A complete listing of composition and properties with S.I units is provided in Appendix B.

Here, table V.1 lists the relevant material properties used in the F.E.A

Property	Value (US units)
Density	9.75e-2 lb/in3
Yield Stress	40 030 PSI
Ultimate Stress	44 962 PSI
Elongation break	8 %
Young s Modulus	10 008 ksI
Poisson s Ratio	0.33

Table 1: aluminum 6061 properties

D. MESH DESIGN

1. Element type

Element type has to be chosen before designing the mesh. The solid element parabolic tetrahedron was selected from the I-DEAS library and used for modeling. It has a three-dimensional typology.

This element type is often used to study parts on which stress, due to local loadings effects, through thickness are considered to be important. Obviously this element supports structural analysis, linear and non-linear.

Moreover, the triangular shape allows easy transitioning in mesh density.

The diagram below shows the shape of parabolic tetrahedron:

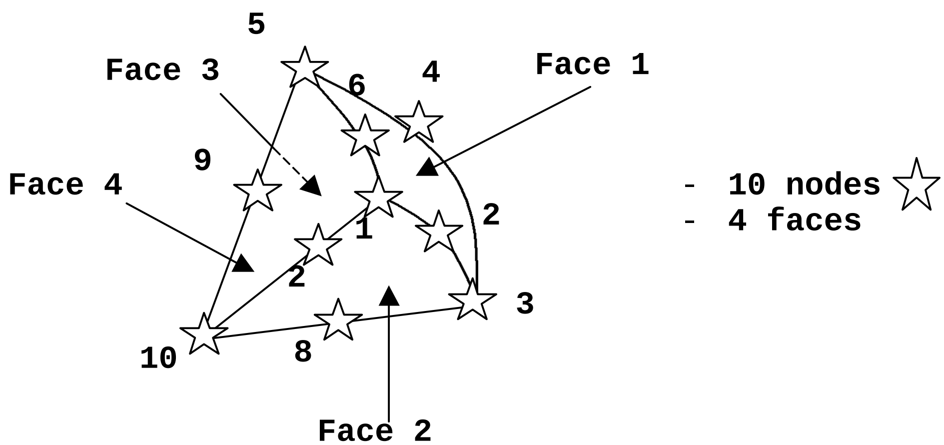


Figure V -2 : schema of the parabolic tetrahedron

2. Meshing part

All the areas of the models have been modeled with the same element.

Meshes of variable density have been used to obtain accurate results. In order to mesh complex parts, the free meshing task was used. Hence the user can create with this tool a refined mesh in the regions of steepest stress gradients. Length element or numbers of elements have to be put in the software. Even if some areas need mesh refined, it is not recommended to use a fine mesh over the whole model.

Care is also required in transitioning of mesh density.

Meshing quality checks allows to avoid troubles in the mesh. They are presented in section F of this chapter.

b. Hatch plate

The whole model of the meshed is shown below. Fine mesh is provided at the intersection with hull contact surface where steep stress gradient is expected. Coarse mesh is built elsewhere.

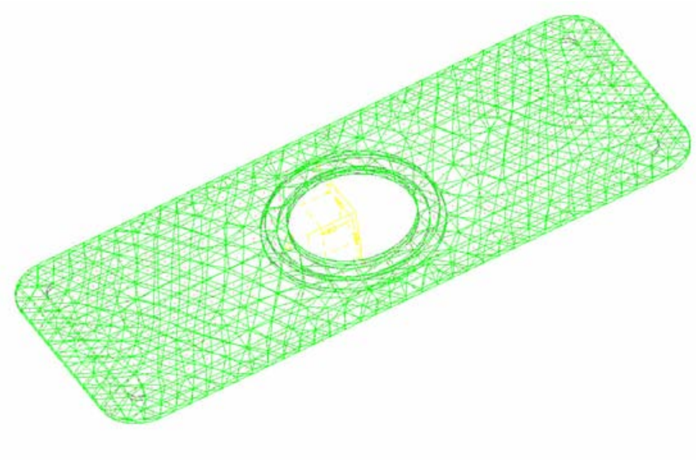


Figure V -3 : the hatch plate mesh

The F.E model contains 6004 nodes and 2840 elements.

c. Hull

The structure has been modeled with a fine mesh in the vicinity of the longitudinal edges (up and low) and in the corners of the contact surface with the hatch plate. Coarse mesh is provided elsewhere.

Several models of the hull are used in the simulation: carter model, half model and whole model. When more detailed stress/displacement results are required it is comfortable using reduced engineering models. They allow to analyze with more precision (mesh refined, reduced time of simulation …) the effects observed.

The picture below shows the carter model meshed with refined mesh in the sensitive areas:

- Corners of the upper surface in contact with the hatch plate
- Curved surfaces transitions between the vertical longitudinal surfaces and horizontal surfaces (bottom or top)

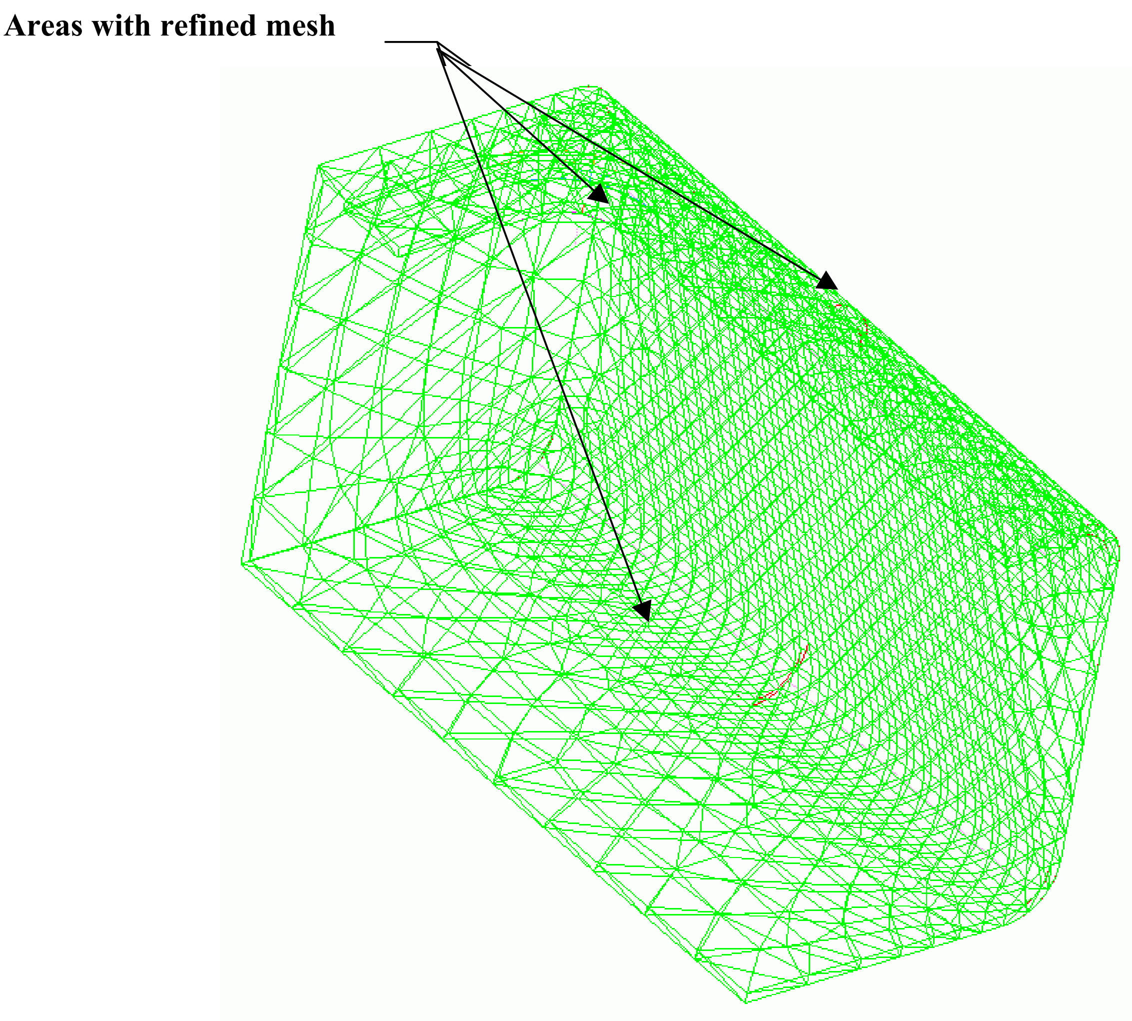


Figure V -4 : the carter mesh model

E FE LOADS AND BOUNDARY CONDITIONS

A boundary condition set (loads, restrains…) has to be defined in the F.E software for solving the problem. Here, loads are assumed to be static.

1. Loads

a. Assumptions

The hydrostatic pressure, due to the weight of the water lying around the ARIES, has to be applied. The hydrostatic pressure increases linearly with depth. It is estimated as follows:

$P_H=\gamma h$ P_H: pressure is force per unit area (PSI)

γ: Specific weight of the liquid (PSI/feet)

h: depth (feet)

γ is given in this study as 0.4447 PSI/feet.

For information the values at 100feet (30m) and 300feet (90m) are:

- h=100feet ⟶ P_H=44.5 PSI
- h=300feet ⟶ P_H=133.5 PSI

Pressure loadings are always directed toward the surface upon which they act and are perpendicular to it.

Effects of salinity and hydrodynamics pressure are insignificant in the loads of the model. Hence, they are not in consideration in this analysis.

b. Hatch plate

The applied load is only hydrostatic pressure on the outside face of the hatch plate.

c. Hull

Same, hydrostatic pressure due to seawater is applied on the outside faces of the hull.

Moreover, as seen above, a pressure occurs on the surface of the hull which back up the hatch plate.

Estimation of this interaction is broke down in two steps: firstly the force applied by the hatch plate has to be evaluated. Knowing this force it is possible to calculate the pressure on the interaction surfaces between the hull and the hatch plate.

- The effect of the hatch plate at a depth called h is equal at a force (Ftot) applied on the center of gravity:

Ftot=W+Fp	W: weight of the hatch plate
	Fp: force due to the hydrostatic pressure

- Weight is given by the relation: W=mg=ρVg where m is the mass, g the acceleration of gravity and ρ the density.

Here the values used for the calculus:
$\rho=9.75e\text{-}2\ lb/in^3$; $V= 89.8\ in^3$; $g=32.2\ feet/second^2$

$\Rightarrow$ W= 8.76 lb = 3.96 kg

- Fp is determined thanks the equation of pressure ($P_H= F/S$) where F is the force, S the surface and P_H the hydrostatic pressure.

As we known P_H at a depth h given ($P_H = \gamma h$) and the surface of the hatch plate in contact with hydrostatic pressure ($S1=319\ inch^2$) we can determine Fp: $Fp=\gamma h S1$

- It results $F_{tot}=F_p + W=\gamma h S1 + W$ where W and the coefficient $\gamma S1$are known

- The force Ftot is distributed over the surface (S2) in contact between the hull and the hatch plate. Hence, there is a uniform pressure (Ptot) estimated by the equation of the pressure: $P_{tot}= F_{tot}/S2$ where $S2=60\ inch^2$

The pressure Ptot increases linearly with depth as follows:

$P_{tot}=(\gamma h S1 + W)/ S2$

$P_{tot}= (\gamma S1/S2)*h + (W/S2)$

The numerical relation between the pressure to apply on these surfaces and the depth is:

$P_{tot}=2.36*h + 0.146$ where h is the depth in feet

The effect of the weight is insignificant.

For information the values at 100feet (30m) and 300feet (90m) are:

- h=100feet ⟶ Ptot=236 PSI
- h=300feet ⟶ Ptot=709PSI

Depth	Oustside face of the hatch plate	Outside faces of the hull	Surface of the hull in contact with hatch plate
100 feet	**44**	**44**	**236**
300 feet	**133**	**133**	**709**

Table 2: summary of the loads

2. Boundary conditions

To solve the F.E model for linear statics, the model must have been properly restrained.

the model.

a. Assumptions

Restrains are u

possibility of rigid body motion. In this F.E.A models are in three-dimensional space so there are three translations and three rotations possible.

ows to analyze just one portion of the structure. The models here have two planes of symmetry. It is possible studying only

have to be the same as the displacements that would have occurred in the whole model because of the symmetry conditions. The following rule has been applied for setting the symmetry conditions:

	Degrees of freedom					
Plane	**X**	**Y**	**Z**	**RX**	**RY**	**RZ**
X=0	**0**	**F**	**F**	**F**	**0**	**0**
Y=0	**F**	**0**	**F**	**0**	**F**	**0**
Z=0	**F**	**F**	**0**	**0**	**0**	**F**

Table 3 : symmetric boundary conditions

X, Y and Z are components of the displacement and RX, RY and RZ are rotations. “F” is used for free and “0” for no motion. By example if the y-z plane (X=0) is the plane of symmetry the followings conditions have to be applied to the nodes (select surfaces or edges) on the plane of symmetry: X=RY=RZ=0 and Y=Z=RX=Free.

b.

➢

depends on the depth of the study.

➢ Restrains: only the surface in contact with the hull is totally restrained.

Symmetric conditions can be applied using the symmetry geometric planes to

with the whole model are presented.

Here are the boundary conditions applied on the whole hatch plate (mesh is not

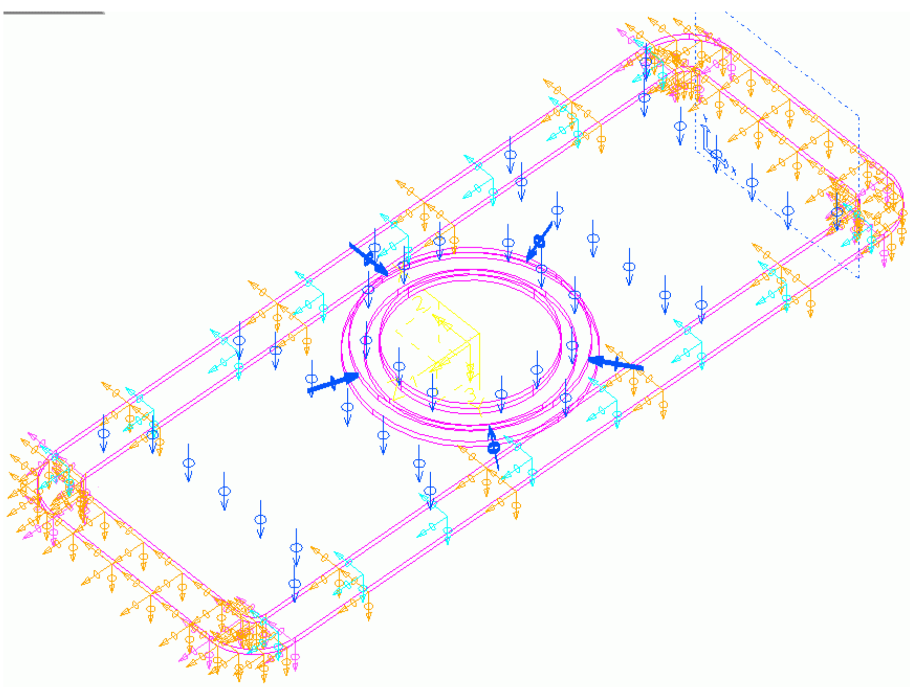


Figure V - : the hatch plate boundary conditions set

surface, the other arrows show the displacement restrains.

c. *Hull*

- Loads: - the hydrostatic pressure is applied on the outside surfaces. Its value depends on the depth of the study.

  - the pressure due to the hatch plate is applied in the surface (S2) in contact with it. Its value is also a linear function of the depth.

- Restrains: the edges on the bottom along axis X are totally restrained for simulating the influence of the unmodelled structure and restraining to the ground.

- Symmetric conditions: For the half model symmetry is assumed about a vertical plane along the longitudinal axis of the ARIES (plane y-z where X=0). To use carter models an other cut is made about the plane x-y (Z=0). It provides translational and rotational restraints about the global axes as shown in the table V.2.

The following pictures show the boundary conditions applied on all kind of models: carter model, half model and whole model. Same are used for the models with strengthening hull.

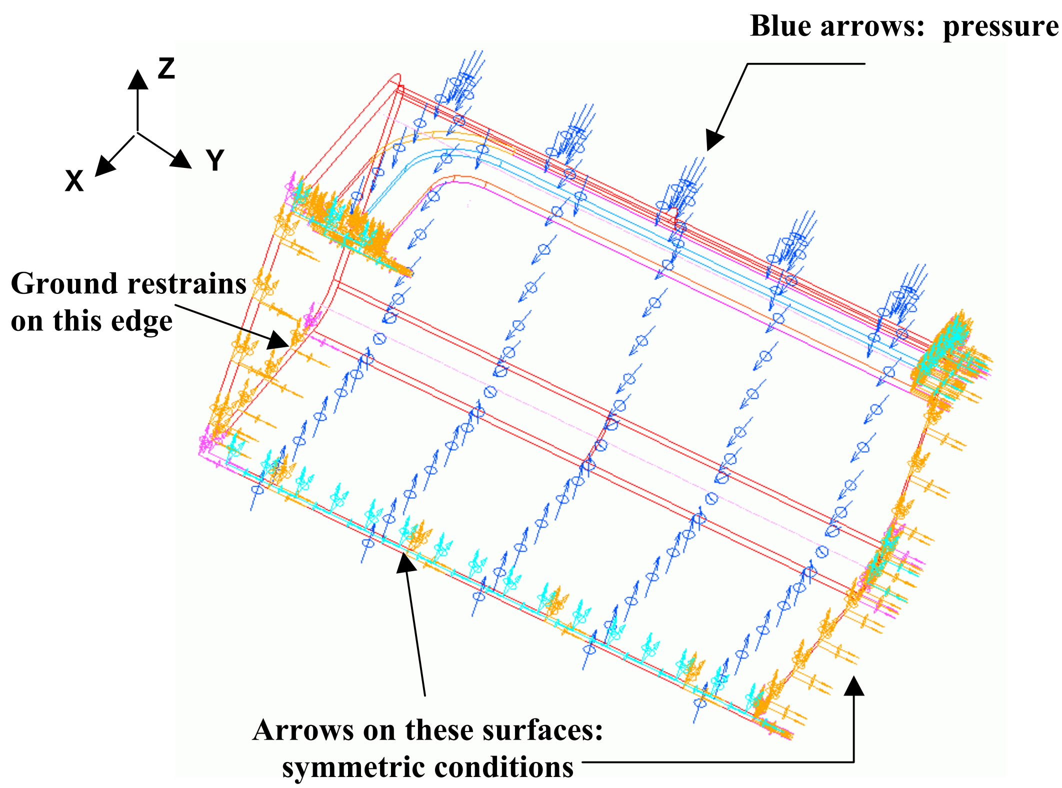
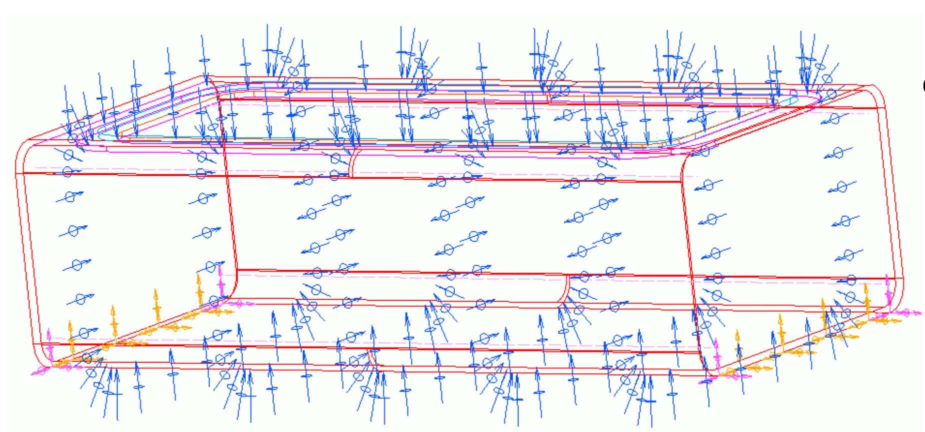


Figure V -6 : carter hull boundary conditions set

Only the restrains and loads are applied on the whole model.

The half model is made thanks the symmetry about the longitudinal plane that it is possible to observe the inside of the hull and the behavior along its entire length.



et

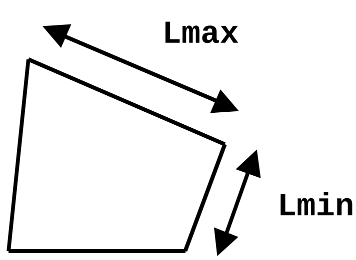
Figure V -7 : whole hull boundary condition set.

Element size	**Depends on the type of analysis**
Interior angles	**Min: 20 degrees; Max 125 degrees**

Table 4 : quality checks

a. Aspect ratio:

It is the ratio between the longest and the shortest element dimensions. The element is deformed for a high value of this ratio.



Aspect ratio= max length/ min length

Figure V -8 **:** Calculation of the aspect ratio.

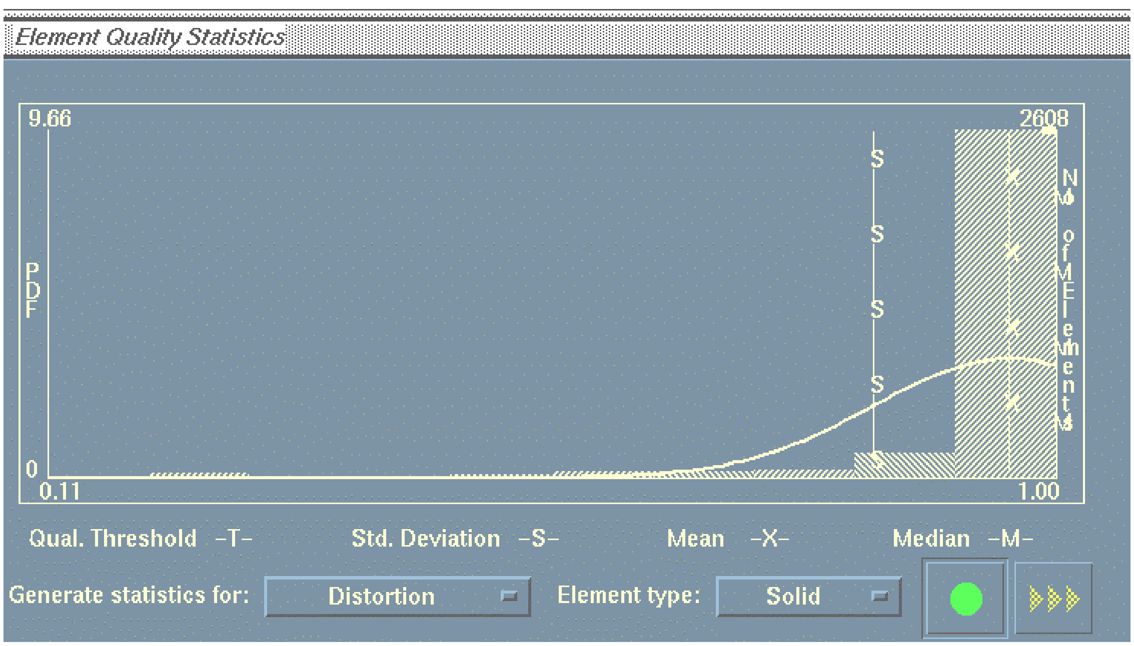
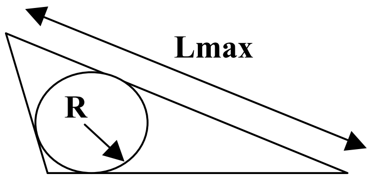


Figure V -9 : example of statistics generated for distortion

Elements of the mesh respect the distortion criterion (distortion > 0.1). Here most of the elements have a value close to 1.

c. Stretch

It measures stretch of elements from an ideal shape. For tetrahedrons the stretch value is calculate as follows: this is the radius (R) of the largest sphere that will inside the element, divided by the longest distance between corner nodes (Lmax). A normalization factor, issued from the target element, ($\sqrt{24}$ for tetrahedrons) is also applied. Any values above 0.1 are acceptable in this F.E.A.



$$Stretch = (R / Lmax) * \sqrt{24}$$

<u>Cutaway of a deformed tetrahedron element</u>

Figure V -10 : Calculation of the stretch factor.

An example of statistics generated for stretch criterion for a carter model of the hull is shown in the next picture:

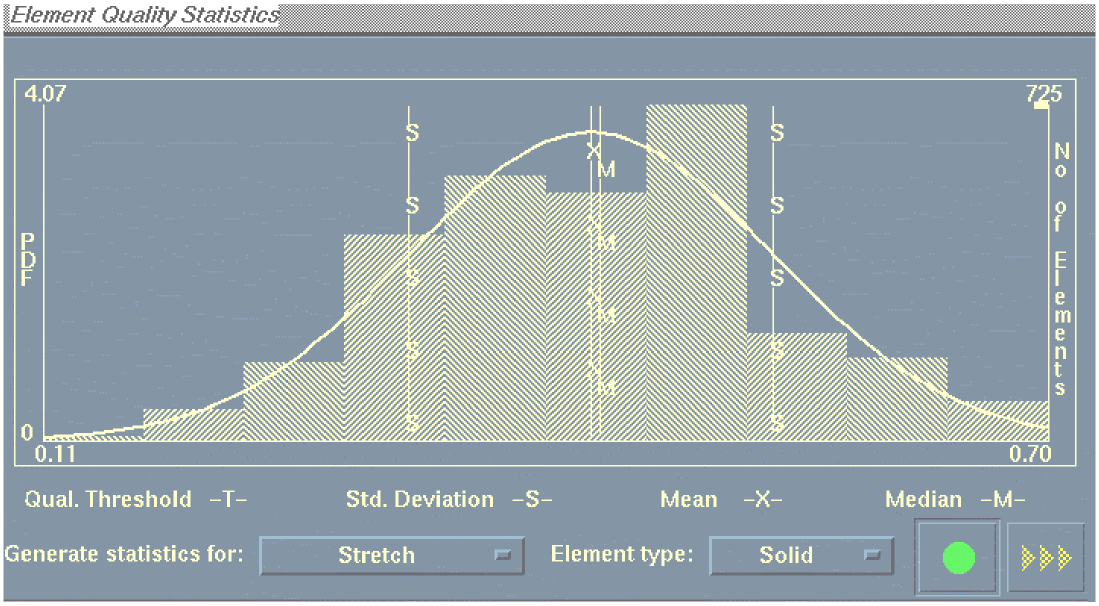


Figure V-11.: Example of statistics generated for stretch

All the elements have a value upper than 0.1, the minimum value fixed for stretch criterion. The average value is 0.3 meaning a correct design of the elements according to stretch.

d. Element size

It measures the minimum and maximum lengths of the edges on an element. This check allows to detect elements with inordinately length edges (too small or too long). Values out of the threshold determined by the user are listed. They are not the same for each simulation. It depends on the element length used.

e. Interior angles

It checks interior angles of elements and lists those that are not in the thresholds defined (minimum=0-60 degrees and maximum=60-180 degrees). Min=20 degrees and Max=150 degrees give an accurate mesh.

f. Mesh transitions

Care is required in transitioning of mesh density. The goal is to minimize large differences in stiffness between adjacent elements when meshing to avoid bad results. If results show too much variation between adjacent elements the mesh should be refined.

2. Pre run checks

Before running calculus, I-DEAS simulation program checks automatically missing variables and nodes or elements not connected to structure. Missing material properties or physicals properties in the filters cancel the simulation. Hence, the user has to complete the databases required.

3. Post run checks

Firstly, I-DEAS provides errors and warnings to prevent poor modeling and bad analysis. They are issued when criteria are violated. This is the first step in post run checks to accomplish. All error and warning messages were investigated and resolved in this analysis.

Secondly a global inspection of the results was performed:

- Comparison with results expected to ensure the results are reasonable.
- Seek the discontinuities in the model.
- Checking the adequacy of the meshing: accurate mesh transitions and size of elements…

VI. ANALYSIS RESULTS

A POST PROCESSING METHOD

Specific magnitudes for various quantities are obtained in the analysis results thanks the post-processor.

1. Displacements results

Displacements represent the motion of the structure. Displacements plotted are exaggerated (maximum is equal at 10% of the screen) to display the difference between deformed and original shape. They consist of translational and rotational degrees of freedom:

$$\{u\} = [K]^{-1}\,\{f\} \qquad \text{where} \quad \begin{cases} u = \text{nodal displacements} \\ K = \text{stiffness matrix} \\ F = \text{nodal forces} \end{cases}$$

2. Stress results

In this F.E.A the primary result parameter of interest is stress. The Equivalent stress acting on the model is plotted when stress display is required. The use of Von Mises stress for checking yield stress was chosen. This criterion is the most used by F.E software because of the simplicity of the expression. The standard equation is:

$$\sigma = (1/\sqrt{\ }2)\ [\ \{(\sigma_X - \sigma_Y)^2 + (\sigma_Y - \sigma_Z)^2 + (\sigma_Z - \sigma_X)^2\} + 6(T^2{}_{XY} + T^2{}_{YZ} + T^2{}_{ZX})\ ]^{1/2}$$

where σ_I are the principal stresses and T_{II} the shear stresses.

B. STRUCTURAL RESPONSE OF THE HATCH PLATE

Figure VI.1 shows the Von Mises stress plot, which give information about the stress repartition and the values recorded. The maximum stress is 35500 PSI at 300feet depth.

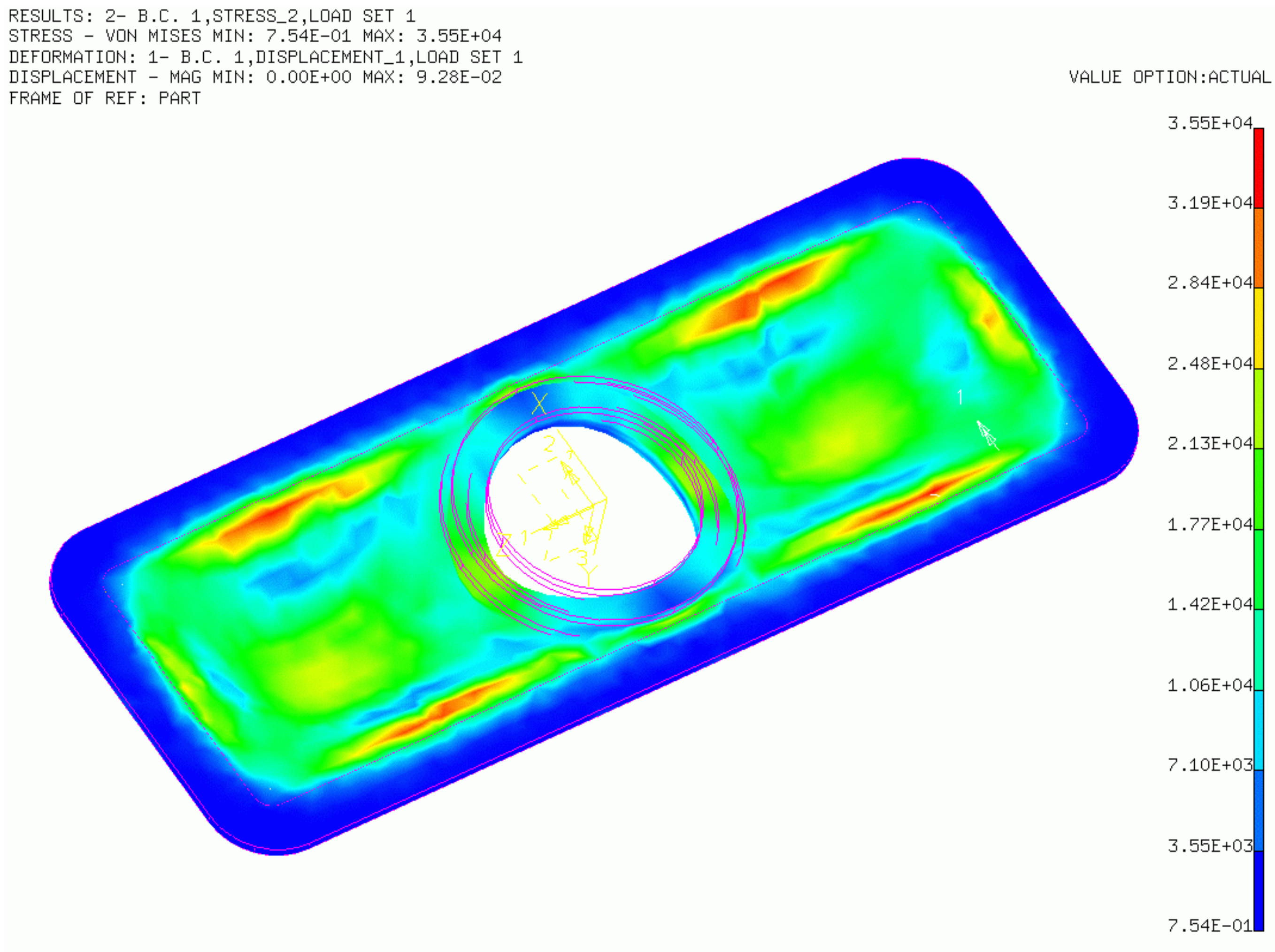


Figure VI -1 : Von Mises stress plot of the hatch plate at 300feet

The values of stresses are below the yield stress.

At the same depth, maximum displacement (vertical displacement) is 0.098 inch. This value is relatively small. The deflected shape of the structure is shown in the figure VI.2 below:

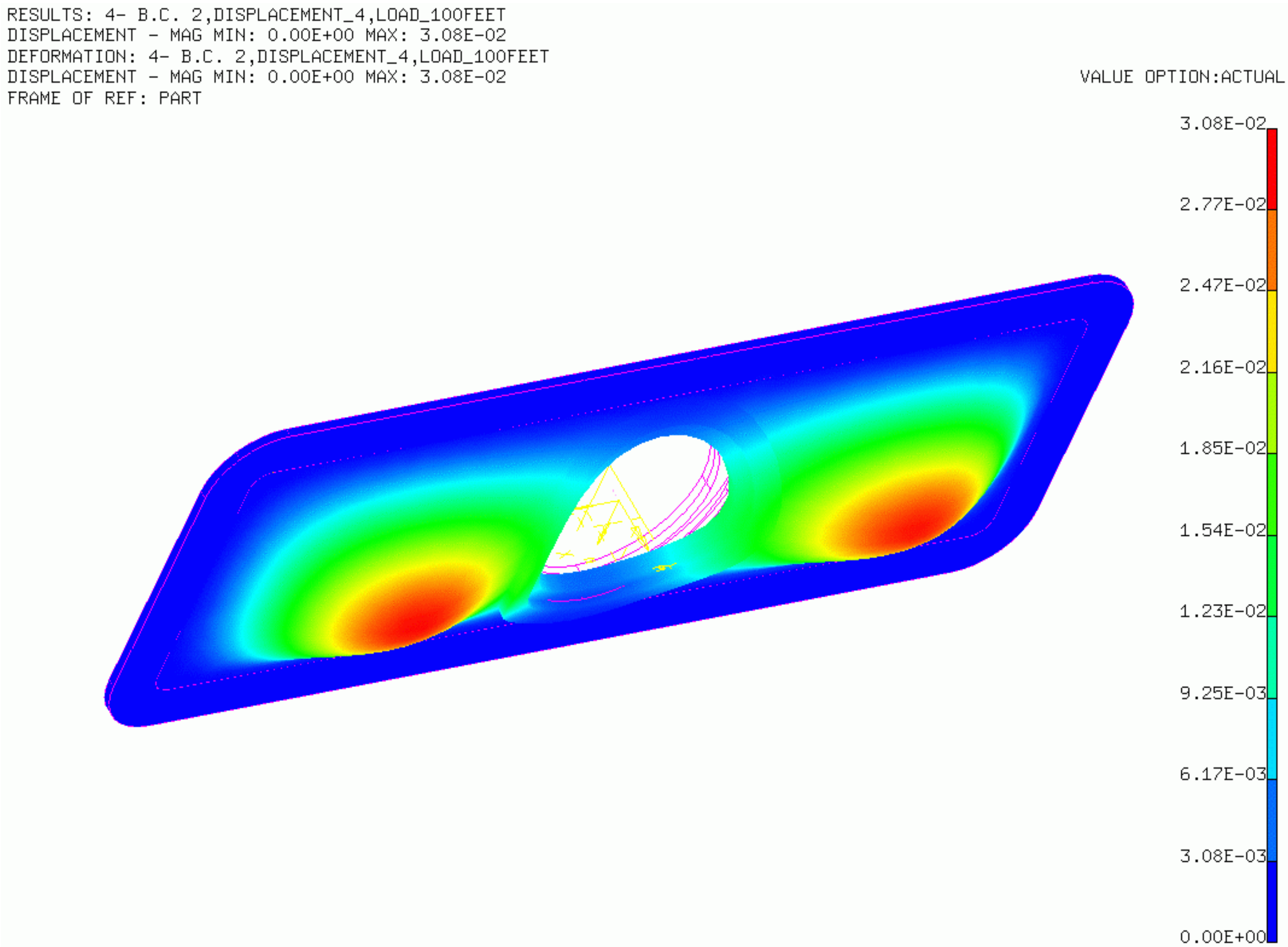


Figure VI -2 : Displacements plot of the hatch plate at 300feet

The results recorded allow to conclude no structural problems will occur on the hatch plate.

C. STRUCTURAL RESPONSE OF THE HULL

The Aries is intended to shallow water operations. First this analysis checks the capability to dive at 100feet current maximum depth of the operations.

1. Checking at 100 feet

The results valid expectations: hydrostatic pressure and hatch plate pressure generate compression and bending of the structure. The figure next page shows the response of the hull at a depth of 100feet. Deflection is exaggerated to visualize the displacements.

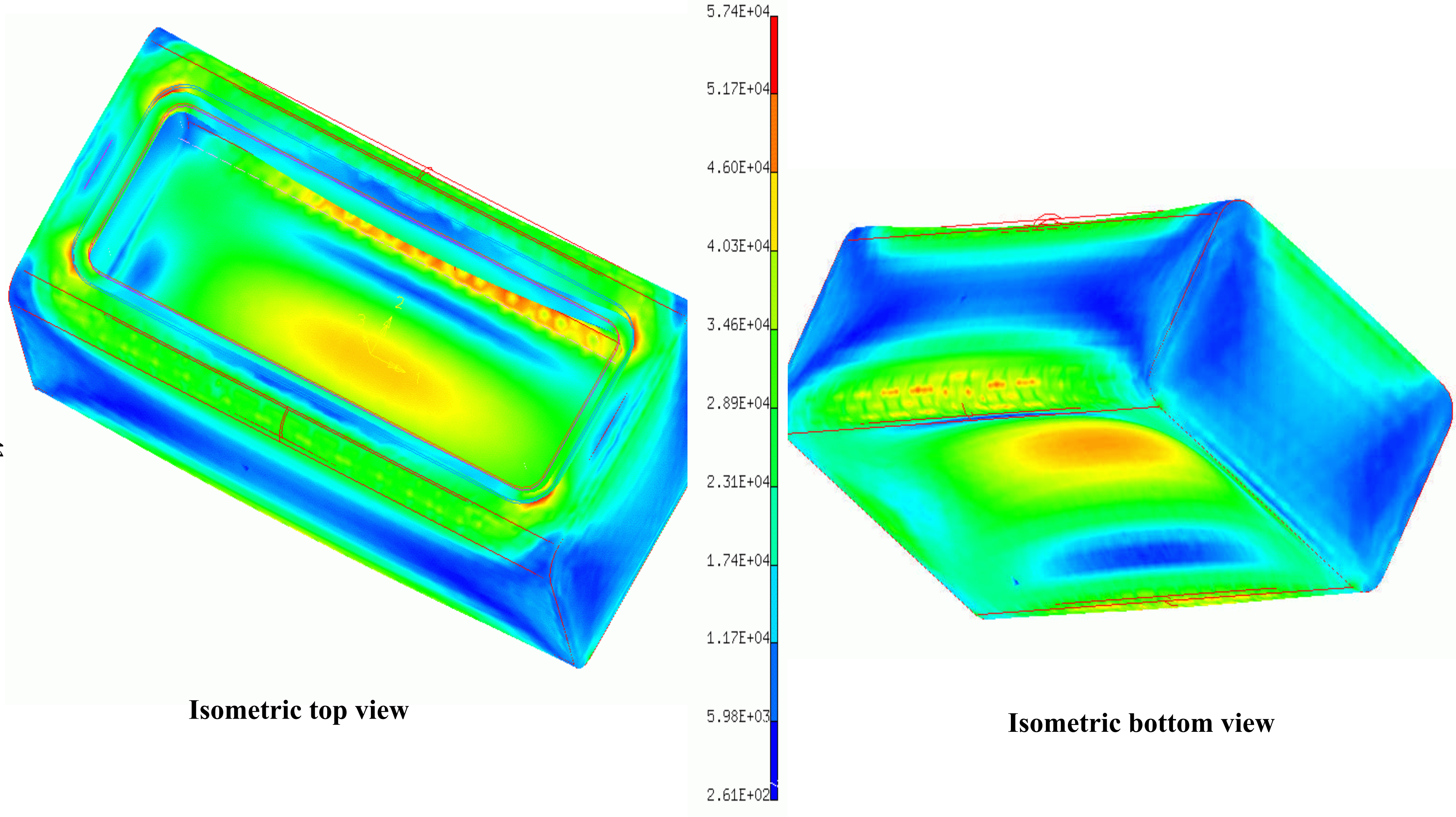
The peak stresses reported (57400PSI) are in the curved transitions between the vertical surfaces and the bottom of the hull. These cylindrical surfaces are very difficult to mesh because of the geometrical shape. They are the houses of the worst elements of the mesh. Even if they respect criteria defined by quality element checks, analysis results here needs lot of precaution.

In the center of the bottom there is the maximum displacement recorded (0.66 inch) and stresses are slightly upper than yield stress.

High stresses are also recorded in the corner on the top faces of the hull in contact with the hatch plate.

There are some of Von Mises stress values past yield stress. They are indicated by yellow and red colors in the graphic. They are very localized so they are considered acceptable.

The results allow to conclude that the structure of the hull resists at loads due to seawater pressure at 100feet. The ARIES has no structural problems in shallow waters. Nevertheless, risks of failures are expected deeper.



Isometric top view

Isometric bottom view

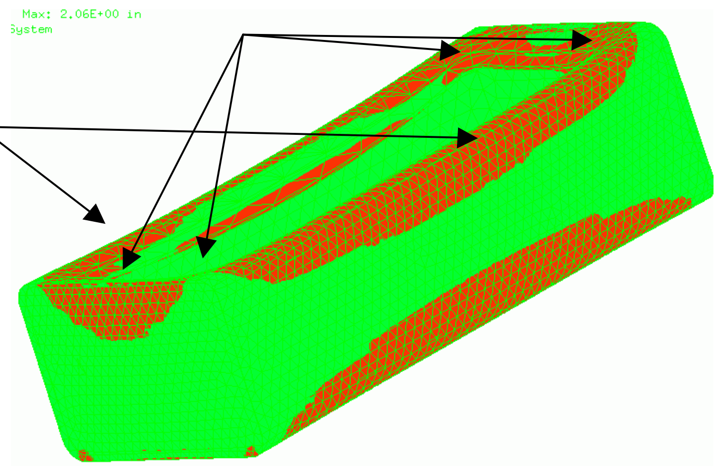
Figure VI.3. : Von Mises Stress plot for a depth of 100feet

2. Checking at 300feet.

The same simulation is performed. Only values of the pressure are changed. The next figure shows stresses past yield stress are recorded in most of regions of the hull. Maximum stresses (1.7.e5 PSI) are located in the vicinity of the corners on the top face of the hull in contact with the hatch plate. Maximum values are also encountered in the low curved transitions. The center of the bottom has a equivalent stress about 1.2e5. The top curved transitions record equivalent stresses about 9e4PSI.

Corners on the top face

top curved transitions



Legend:

Green: below yield stress

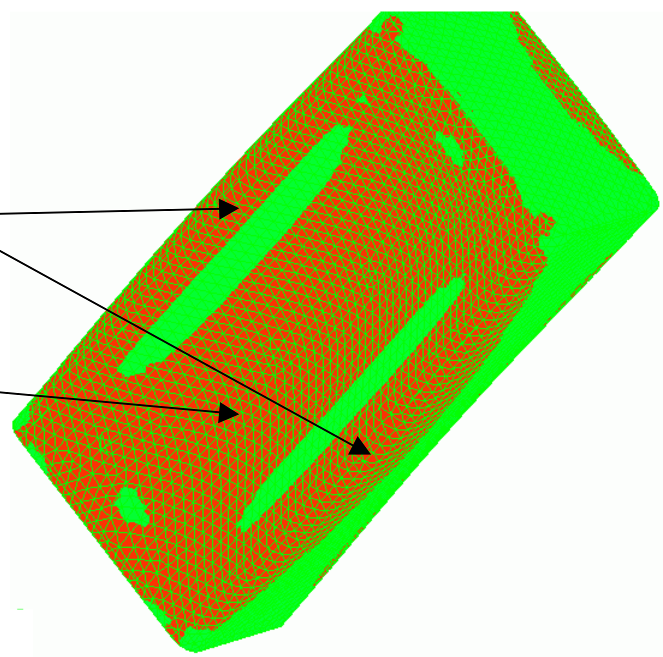
Red: over yield stress

Isometric view

Figure VI -4 : Von Mises stress plot of the hull at 300feet

low curved transitions

Center of the bottom



Isometric bottom view

The values recorded are unacceptable. Hence, the ARIES cannot operate at 300depth. The structure will be highly damaged by the effects of the static pressure. The next figure shows the deflection results.. Displacement values indicated in the horizontal faces (bottom and top face) are very high. Vertical faces have a low bending

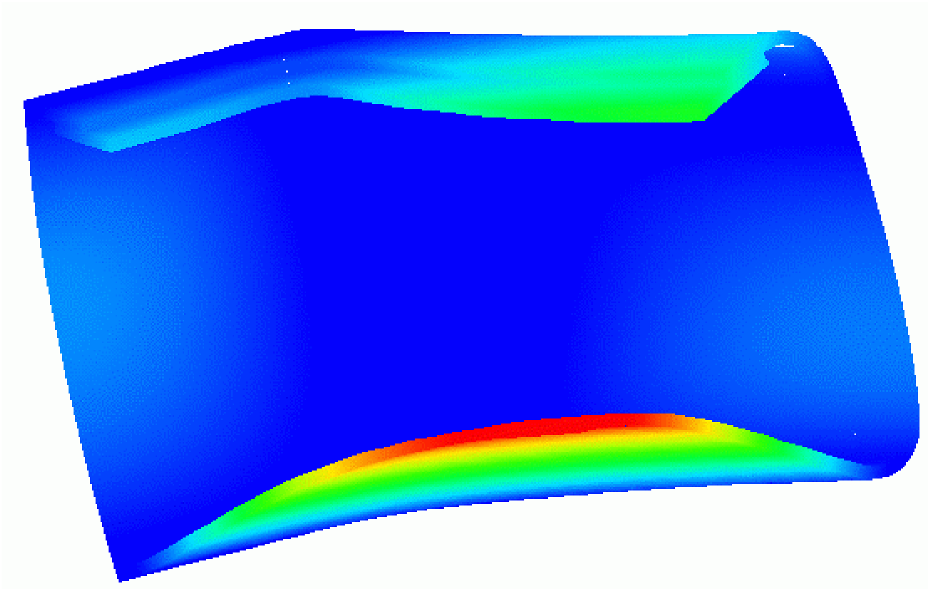
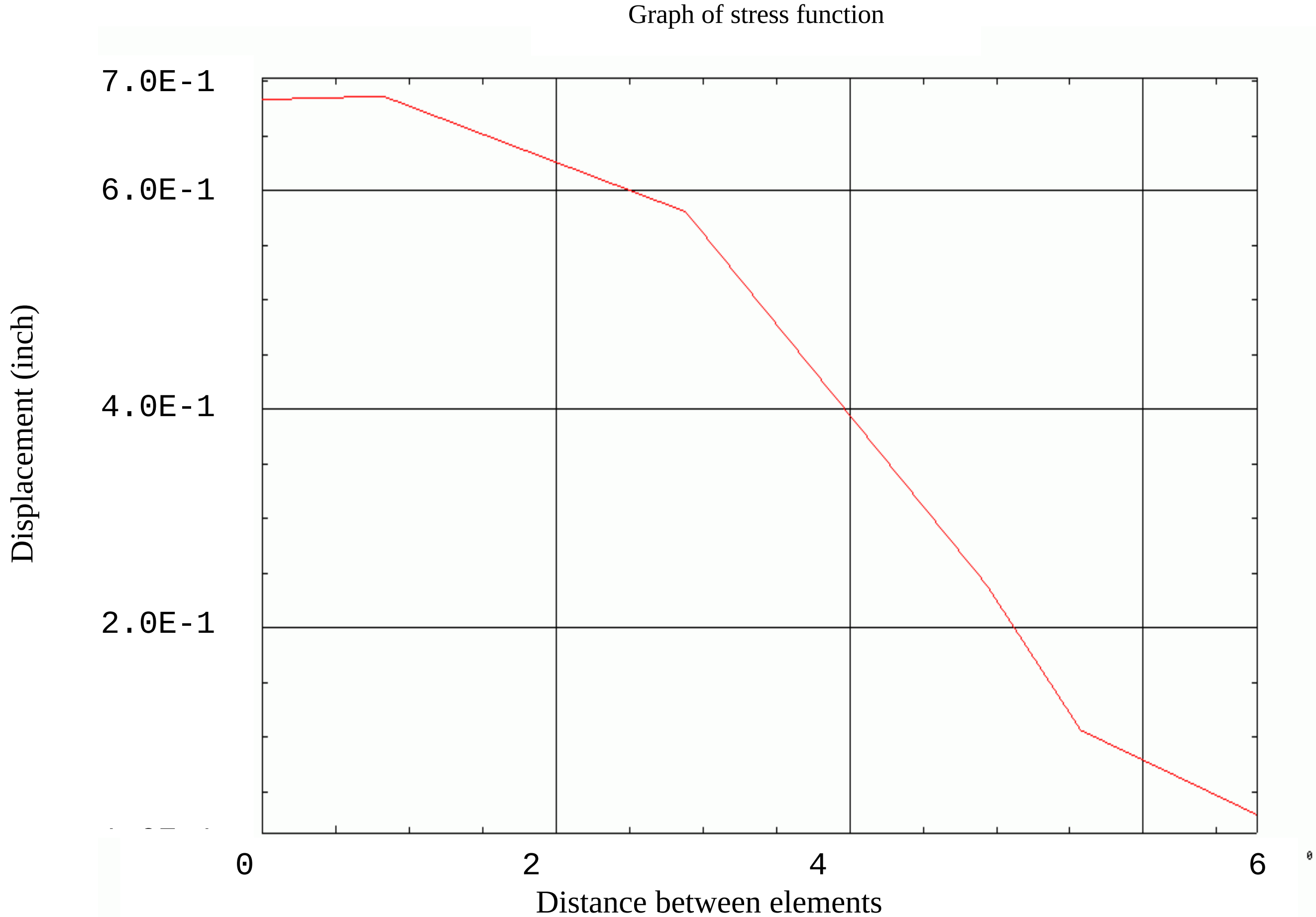


Figure VI -5: Displacement plot of the hull at 300feet

The main problem about deflection is in the bottom. The peak displacement is 0.68 inch at the center of the bottom. The structure is subject to high bending. The top face under the pressure is compressed and has a maximal displacement of 0.4”.

The diagram next page, table VI.1, indicates the decrease of the displacement according the axis X of the analysis. In abciss there is the distance between elements picked up for making the graph and in ordonnee there is the value of the displacement recorded at the elements. Elements picked up are in the bottom. The graph starts from the center of the bottom (high displacement) to the low curved transitions (weak displacement).

Graph of stress function



Displacement Top surface

Table 5: graph of displacement function in the top face

D. HULL STRENGTHENING

1. Set up of vertical beam

The purpose of using vertical beams is to reduce stresses in the corners of the top face. Beneath each corner a beam is implanted. The next figure shows what kind of beam is used:

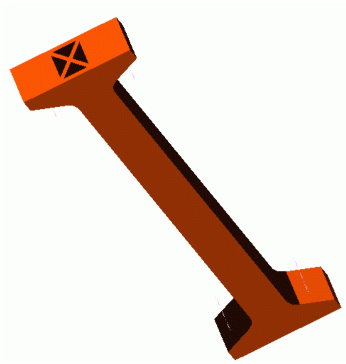


Figure VI -6 : Vertical beam

The beam (0.5x0.5) is hollowed inside and 9.25 inch high. The surfaces in contact with the hull are 1.5 inch wide.

. The use of vertical beams is attractive to reinforce the top face. The hull stiffened with this system will have no structural problem in the corners of the top face. Stresses and displacements are reduced: stresses are in the limit of the criteria (past values are very localized) and displacements are below 0.05 inch. Stresses in the top curved transitions are reduced but there are still above the yield stress.

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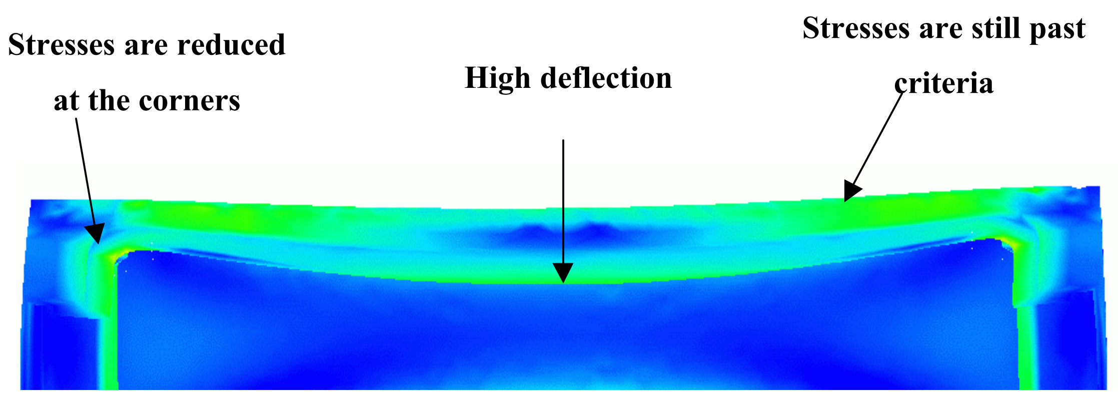


Figure VI -7: top surface stiffened by vertical beams

The figure below is a zoom of the corners of the hull and indicates some stress values:

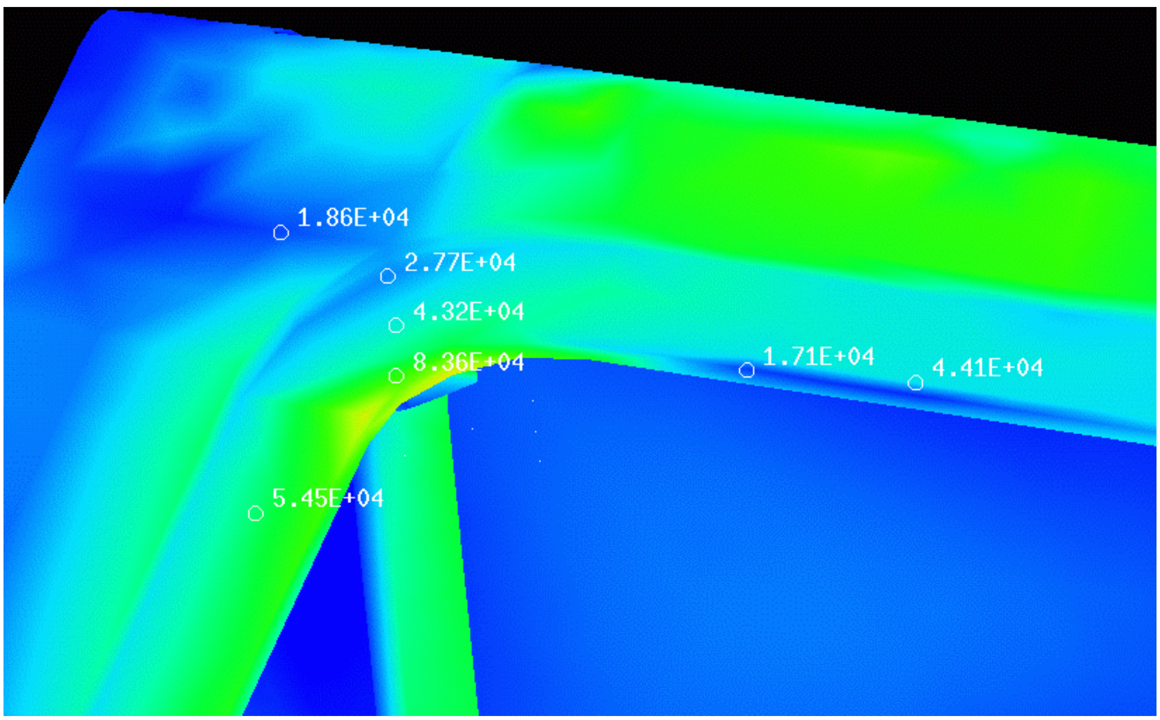


Figure VI -8: zoom of the corners

Nevertheless a vertical beam is needed in the middle of the top face to avoid the deflection (0.6 inch). This solution resolves only the problems in the corners and not for the whole top surface. The disadvantage with setting up an other beam is that lot of space available is lost. But deflection decreases a lot (0.1 inch).

2. Set up of ribs

A solution for strengthening the hull is to dispose ribs under the top plate and above the bottom. The goal is to reduce stress in the curved transitions and in the top face. Ribs used are in aluminum 6061, 0.3” wide, 3” long, 2” high and are hollowed inside (0.2” thick).

. The next picture shows where they are located.

More ribs can be used to get a stiffened hull. They are welded all around the hull.

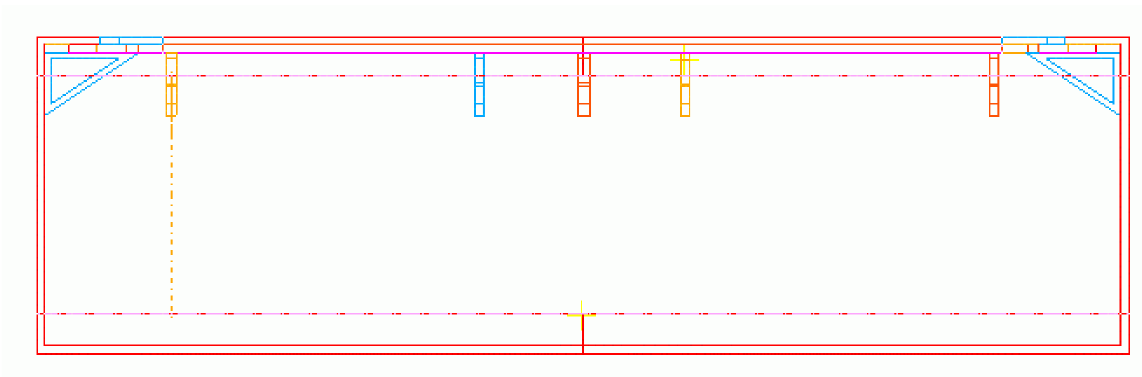
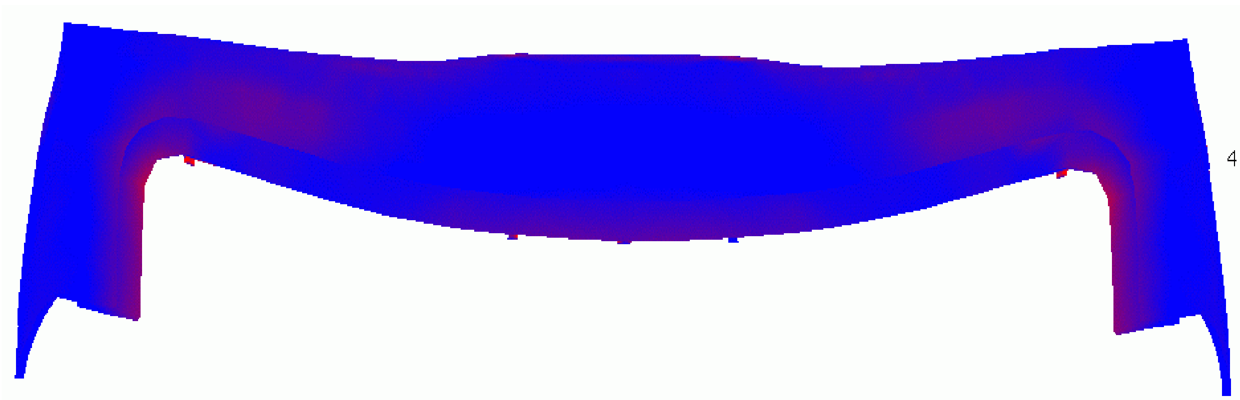


Figure VI -9: hull with ribs (only beneath the top face)

Results shown on figure VI.10 are plotted only for the top of the hull



Legend: red > 41 000 PSI

Blue < 41 000 PSI

Figure VI -10: Von Mises Stress plot: top of the hull with ribs

Most of the structure is colored by blue. There are still some parts above the yield stress. The maximum stress in the top of the hull is 57 000 PSI. Whereas it is very localized, the structure is able with these stiffeners to dive until 300 feet. Nevertheless it requires precaution.

When designed with several ribs in the low of the hull, stresses in the low curved transition decrease also.

3. Set up of plates

A solution with plates is tested here. Plates from the bottom to underneath of top face are welded to the longitudinal face. They are in aluminum 6061, 0.3” thick.

They strengthen the inside of the curved transitions. The first solution, vertical beams beneath corners, is used with these plates for the analysis.

The shape of the hull is shown in the figure below:

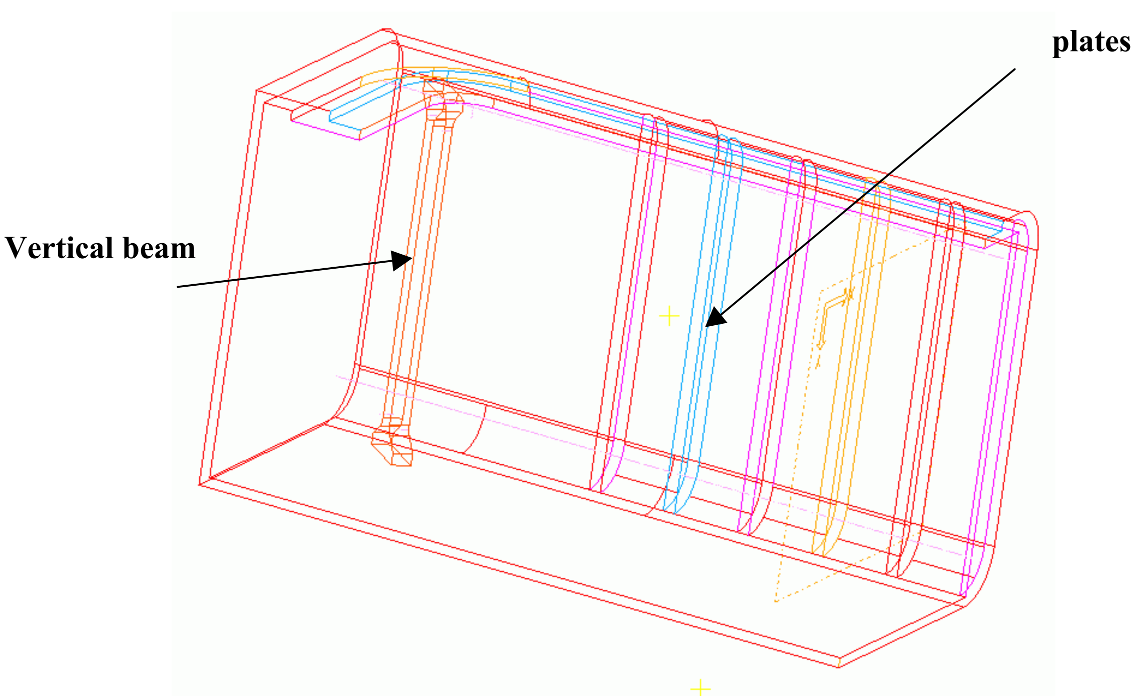


Figure VI -11: design of the hull with stiffeners plates

The top of the model is well stiffened. The maximum value in the top curved transitions is lower than 35 000PSI. There are still values past yield stress (until 55 000 PSI) at the borders of the top face but it seems no structural problems will occur. Deflection is relatively low (0.2”).

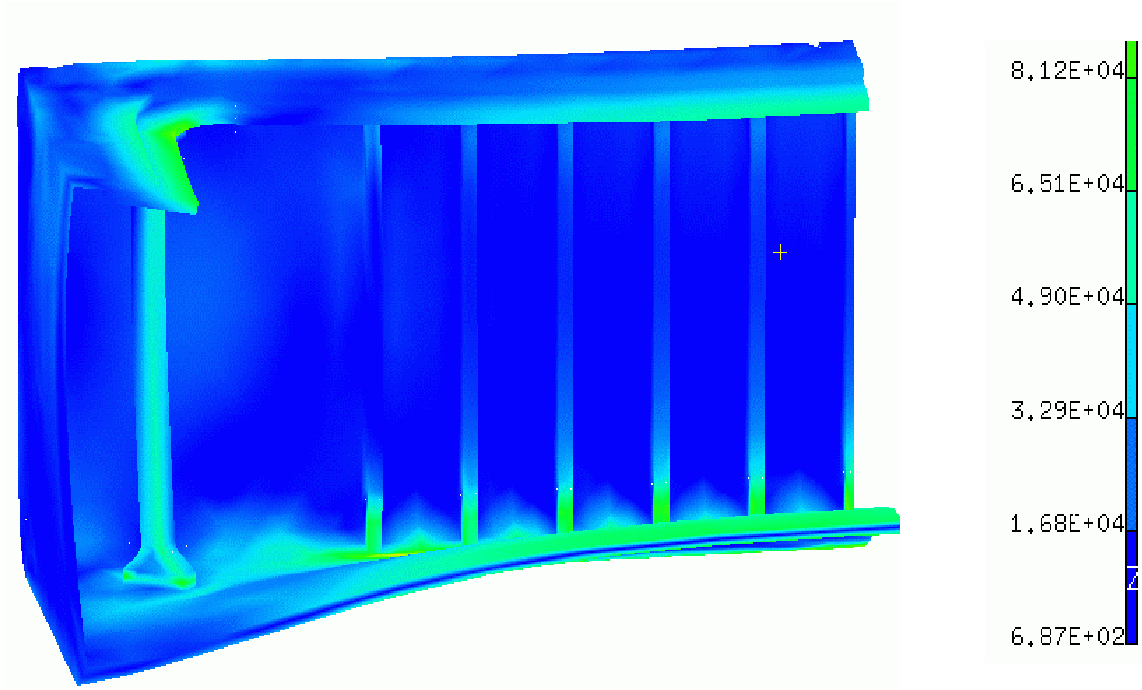
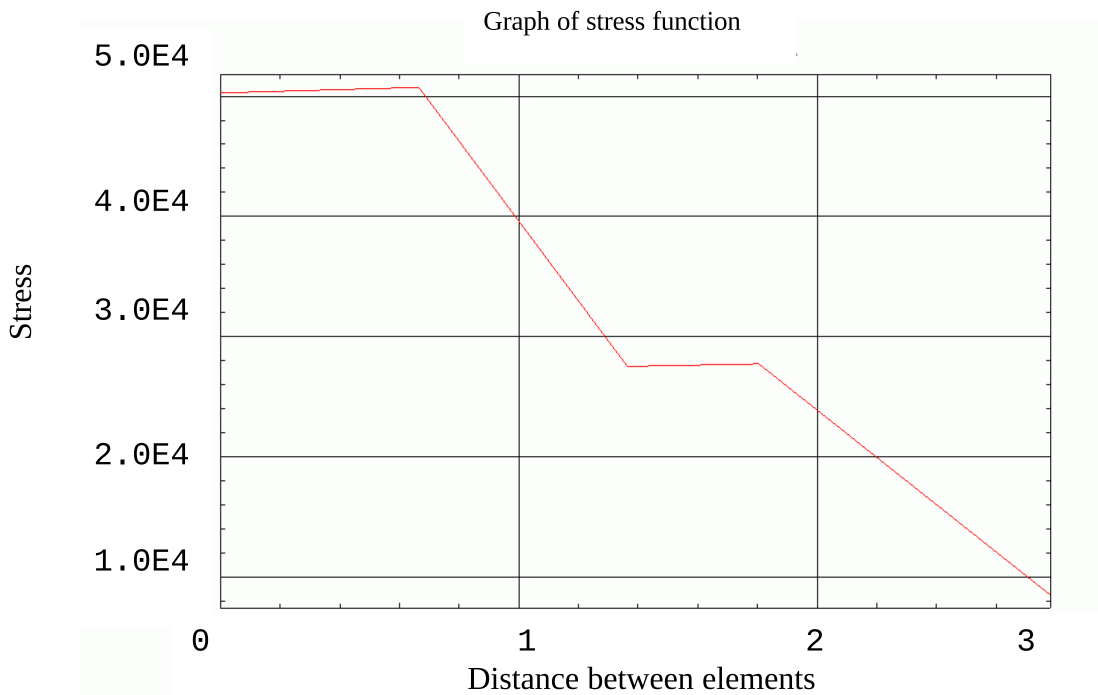


Figure VI -12: Von Mises Stress plot: hull stiffened with plates

In the low part of the model high stresses and high displacements are not eliminated. The peak stress is 75 000 PSI in the curved transitions and the deflection of the bottom is resolved. This kind of stiffeners increases the stiffness of the structure. They allow to reduce stress but this is not enough.

The diagram next page shows the stress values recorded on elements on the top face from the border to the lateral face. It confirms stresses in top curved transitions are low but there are near the yield stress and past in the vicinity of the borders.



Von Mises Stress Top surface

border **Limit with the longitudinal face**

Table 6: graph of stress function in the top face

4. Set up of Tbeams

The solutions performed above are intended to solve structural problems about the top face and curve transitions. Their effects on the bottom are not important. Deflection and stresses are always very high in the center of the bottom (max: 1.7e5 PSI and 0.8”)

A solution to reinforce the bottom of the hull consists to set up Tbeams in this place. It completes the previous solution. Many Tbeams are required in the center to get the hull stiffened.

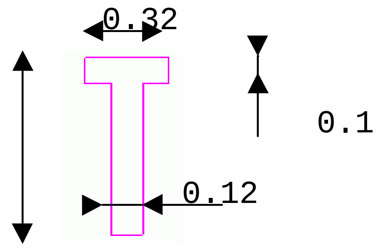
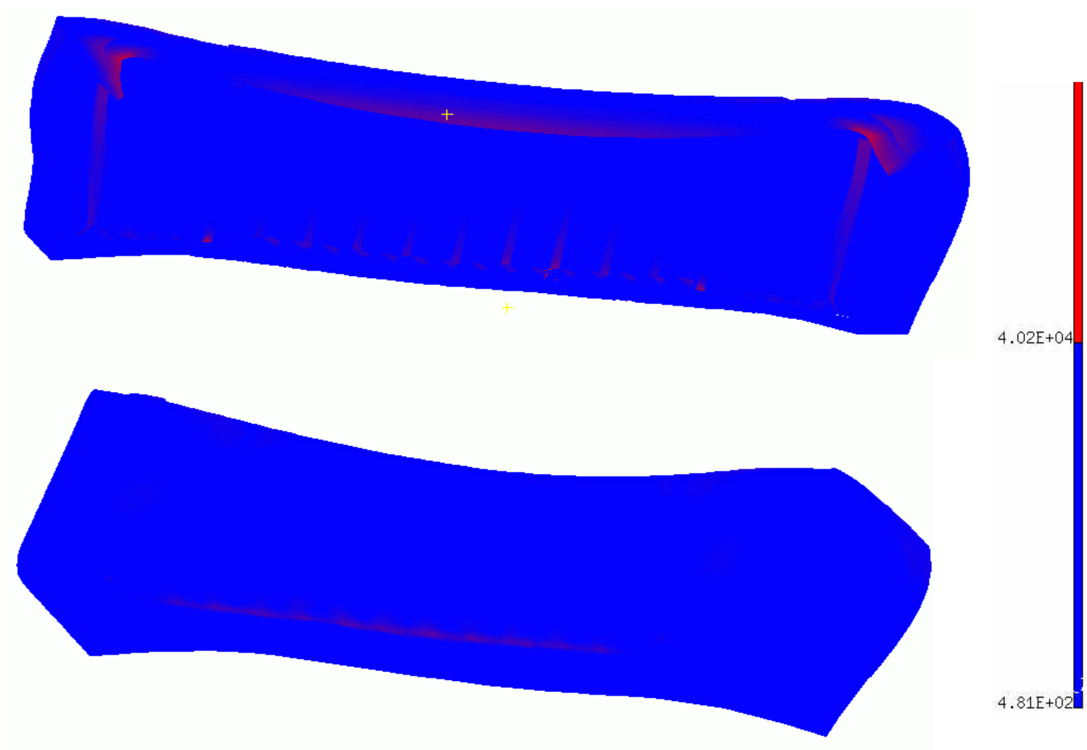


Figure VI -13: Tbeam dimensions

Front view

Bottom view



Legend: blue < below yield stress

Red > yield stress

Figure VI -14 : Von Mises stress plot: hull stiffened with Tbeams

The previous figures show stresses recorded on the structure are below the yield stress except in very localized areas. No high stresses occur in the bottom and in the curved transitions, defined as sensitive areas.

The high stresses (peak = 1.2e5 PSI) are probably due to a non-accurate mesh in these areas.

Tbeams are a good solution to restrain displacements in the bottom and to reduce stresses. The stiffened hull allows to operate in deep diving depth. But, the use of the AUV at 300feet requires precaution but it is possible to dive at this depth.

The next figure is the displacement plot for this solution. The deflection decreases sensitively in the bottom. The maximum value recorded in the bottom is 0.07”. The displacement in the middle of the top face is still important. Welding ribs beneath the middle of the top face (ie part2 of this chapter) can reduce it

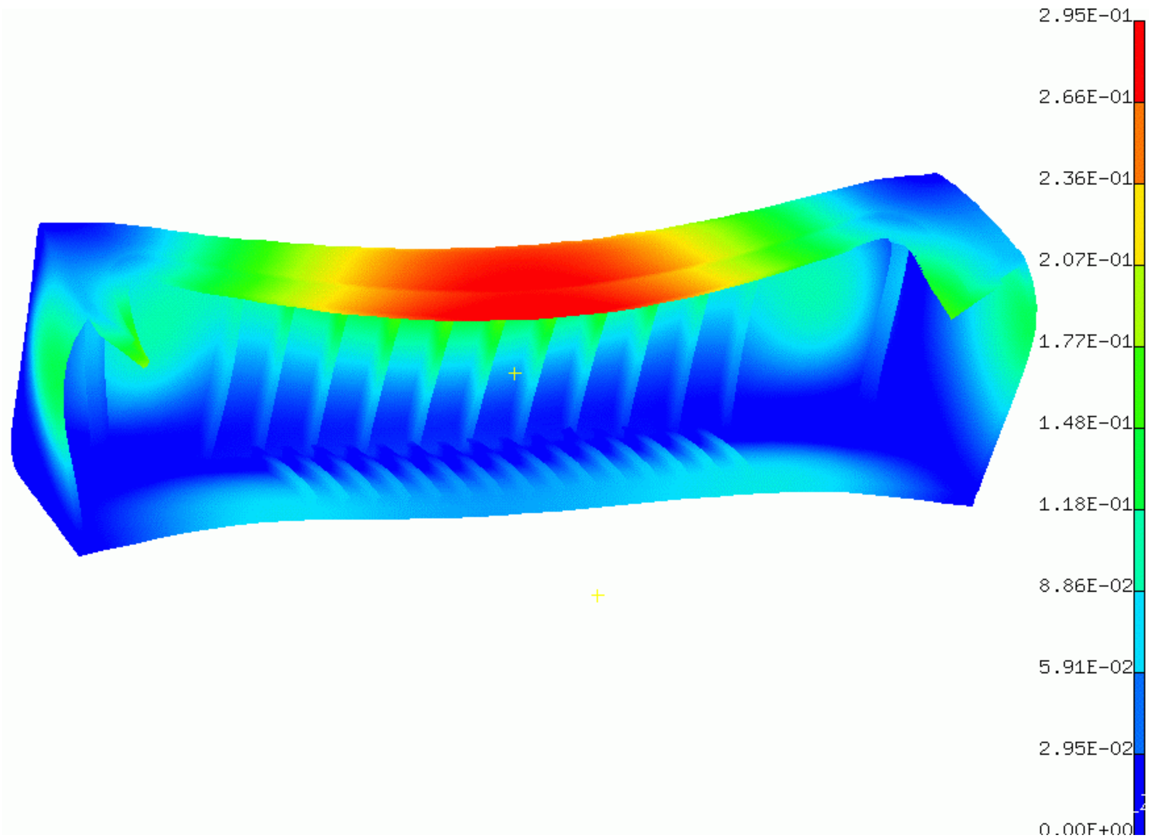


Figure VI -15 : Displacement plot: hull stiffened with Tbeams

5. Redesign

This part of the analysis is intended to test some configurations for a general hull design. These solutions cannot be implanted to the current hull. It provides a way to strengthening the future hull.

Whereas improvements are required in the curved transitions, the design below is a solution to avoid high stresses in theses areas.

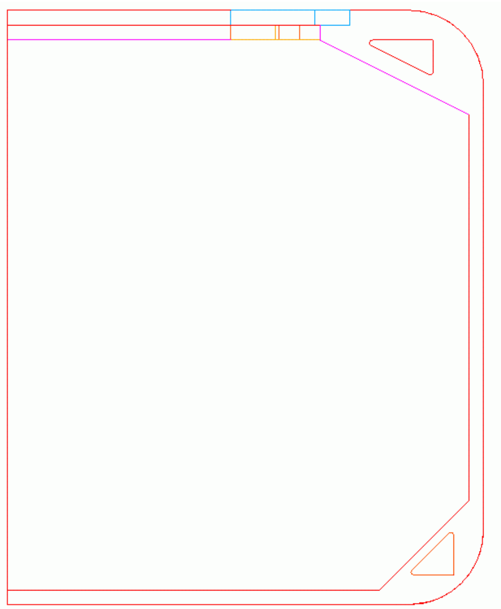


Figure VI-16: Midbody new design frame

Nevertheless this model needs further investigation. First estimations give good results about strengthening the top face, but some problems occur in the low of the hull. Moreover the bottom requires more stiffeners such as Tbeams.

VII CONCLUSIONS AND RECOMMENDATIONS

A CONCLUSIONS

This report provides information about a FEA of the ARIES hull. Its purpose was to check if the structure withstands sea pressure at depth. Designing a FE model requires experience and methodology. Key components of the FE process, loads and boundary conditions, values chosen for the checks are presented.

The ARIES can operate safely in shallow waters until 100feet. Deeper operations require hull strengthening. Indeed, the current hull design doesn't allow to dive safely beneath 100 feet. At 300 feet, the hull is subject to high stresses, high displacements and high bending moments. Most of the values recorded are past criteria defined.

Different solutions have been tested to reinforce the hull in order to reduce stresses and displacements generated.

A vertical beam needs to be added under the corners of the top surface. It is possible to weld some ribs beneath the top surface and on the bottom.

The use of ribs reduces efficiently the stresses generated in the longitudinal edges (up and down). Also, vertical plates with small thickness can be used. These plates are located in the longitudinal surfaces from the bottom to the top. This solution gets the hull rigid and reinforces the edges. It seems this is a good way for strengthening the hull.

Tbeams have been set up in the bottom. It is recommended to put a high density of Tbeams in the center where displacements are very important.

Finally, some solutions are provided about the optimization of the hull design. This is possible to strengthening the hull by modifying its design in the sensitive regions

B RECOMMENDATIONS FOR FUTURE WORK

The model with Tbeams needs further investigation: a beam analysis could be performed. It is also possible to improve the model by meshing with two or three different elements

A buckling analysis will allow to know precisely the depth limit and which critical loads bring to failure. Moreover, the model using non-linear condition will give better results for stress past yield stress. A modification of the hull thickness can be tested through a buckling analysis.

The effects of the time and fatigue can be investigated. A dynamic solution and a fatigue analysis could evaluate dynamic response of the structure, natural frequencies and mode shapes.

When simulation will be completed, the next step will be to test by prototyping the strength of hull modified.

APPENDIX A: ACRONYMS

AUV	Autonomous Underwater Vehicle
ARIES	Acoustic Radio Interactive Exploratory Server
NPS	Naval Postgraduate School
F.E	Finite element
F.E.A	Finite element analysis
F.E.M	Finite element model
GPS	Global Positioning System

APPENDIX B: ALUMINUM 6061

This appendix provides an overview of the material used to make the hull of the ARIES. Source: http://www.matweb.com, online materials information resource

Subcategory: Aluminum Alloy; Nonferrous Metal; 6000 Series Aluminum Alloy

Composition:

Component Wt. %	Component Wt. %	Component Wt. %
Al 98	Fe Max 0.7	Si 0.4 - 0.8
Cr 0.04 - 0.35	Mg 0.8 - 1.2	Ti Max 0.15
Cu 0.15 - 0.4	Mn Max 0.15	Zn Max 0.25

Material Notes: Weldability = A; Stress Corrosion Cracking Resistance = A; General Corrosion Resistance = B (A = best; E = worst). General 6061 characteristics and uses: Excellent joining characteristics, good acceptance of applied coatings. Combines relatively high strength, good workability, and high resistance to corrosion; widely available.

PHYSICAL PROPERTIES	VALUES	COMMENTS	US Units
Density, g/cc	**2.71**		**9.75e-2 lb/ft^3-**
Hardness, Brinell	**120**	**500 kg load/10 mm ball**	**120**
Hardness, Knoop	**150**	**Estimated from Brinell**	**150**
Hardness, Rockwell A	**46.8**	**Estimated from Brinell**	**46.8**
Hardness, Rockwell B	**75**	**Estimated from Brinell**	**75**
Hardness, Vickers	**136**	**Estimated from Brinell**	**136**
MECHANICAL PROPERTIES	**VALUES**	**COMMENTS**	
Tensile Strength, Ultimate, MPa	**310**	**Minimum value**	**44,962 PSI**

Tensile Strength, Yield, MPa	**276**	**Minimum Value**	**40,030 PSI**
Elongation %; break	**8%**		**8 %**
Modulus of Elasticity, GPa	**69**	**Average of Tension and Compression. In Aluminum alloys, the compressive modulus is typically 2% greater than the tensile modulus**	10,008 ksi
Poissons Ratio	**0.33**	**Estimated from trends in similar Al alloys.**	**0.33**
Machinability, %	**50**	**0-100 Scale (A=90; B=70; C=50; D=30; E=10)**	**50**
Shear Modulus, GPa	**26**	**Estimated from similar Al alloys.**	**3,770 ksi**
Shear Strength, MPa	**185**	**Estimated from ultimate tensile strength**	
THERMAL PROPERTIES	**VALUES**	**COMMENTS**	**US Units**
CTE, linear 20°C, µm/m-°C	**23.6**	**average over 20-100°C**	**13 µin/in F**
CTE, linear 250°C, µm/m-°C	**25.2**	**Estimated from trends in similar Al alloys. 20-300°C.**	**14 µin/in F**
Heat Capacity, J/g-°C	**0.896**		**0.21 BTU/lb F**
Thermal Conductivity, W/m-K	**170**		**1,180 BTU in/hr ft^2 F**
Melting Point, °C	**582**	**Solidus**	**1,080 °F**
Solidus, °C	**582**		**1,080 °F**
ELECTRICAL PROPERTIES	**VALUES**	**COMMENTS**	**US Units**
Electrical Resistivity, Ohm-cm	**0.0000037**		**0.0000037 Ohm-cm**

APPENDIX C: I-DEAS FILES

I-DEAS files are available in the computer laboratory of the mechanical engineering hall on the octane 3

Directory: vault5/abeis/FEA

Inside this directory there are two sub directories:

Plate: FEA of the hatch plate

Hull: FEA of the hull

All the files inside each directory regroups the FEA performed

- Plate:

There is only one file: plate_mesh_V3

- Hull

- File: carter: FEA of the carter hull
- File: whole: FEA of the whole hull without stiffeners
- File: modif: FEA of the hull stiffened

For the last file (modif) there are a lot of analyses. Explicit names are given for each solution tested. For example, results of the simulation made for the hull stiffened with plates are named “ solution_plates_half_model”

Steps to check results and read the simulation made:

- Run I-DEAS: simulation, post processing task
- Load the file required
- Display the results: use display icon 2.1, select all elements then done
- Check the value on a element: pick up the probe icon 2.3, move the cursor on the point of the structure

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